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REECOL Ecological rehabilitation and long term
monitoring of post mining areas

Deliverable 4.4

Analysis of revegetation options including plants for industrial uses

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1. Introduction

The transformation of post-mining regions in Europe, particularly areas degraded by hard coal and lignite mining, represents one of the key environmental, spatial, and socio-economic challenges in the context of the European Green Deal and the climate neutral policy. The reclamation of post-industrial land can no longer be perceived solely as a technical process of restoring utility functions, but rather as an opportunity-driven, multidimensional activity integrating environmental, climatic, productive, and landscape aspects.

In this context, agricultural use of post-mining land is gaining particular importance, including its utilization for industrial and energy crops. These crops, characterized by relatively low requirements, high tolerance to environmental stress, and the ability to produce large amounts of biomass, are increasingly identified in the literature as a viable alternative to conventional food-oriented agriculture on degraded land. At the same time, they can perform important environmental functions, such as improving the physical and biological properties of soils, increasing water retention, reducing erosion, regulating contaminants (phytoremediation) and enhancing soil organic carbon (SOC) sequestration, which directly aligns with climate change adaptation and mitigation objectives.

The *Task 4.4 Analysis of revegetation possibilities regarding future land uses* - implemented within the REECOL project was designed as an element linking theoretical analyses with application-oriented tests, enabling verification of the reclamation potential of selected solutions under real conditions. The scope of work included both a review of current sectoral knowledge regarding the performance of industrial and energy crops on post-mining land, as well as field studies on the impact of biologically active compost application on soil properties and soil-plant-contaminant interactions.

The implementation of the task was essentially divided into two complementary parts:

- PART I (*Chapters 2-3*) comprises theoretical considerations regarding the potential of non-food agricultural use of reclaimed land, with particular emphasis on industrial and energy crops. This section presents these crops as a potential reclamation direction, or temporary reclamation pathway, highlighting their advantages compared to conventional food-oriented agriculture, and discusses the functions they may perform on degraded and contaminated sites, including phytoremediation, CO₂ sequestration and soil stabilization. These considerations were additionally related to the specificity of selected post-mining regions, such as Velenje, where the scale of land transformation and geomorphological and geochemical conditions may determine hypothetical land-use scenarios.
- PART II - distinct part of the task (*Chapters 4-6*) - focuses on application tests of compost (an innovative product developed under *Task 4.3* of the REECOL Project) conducted at three study sites: Konin, Velenje, and Mazingarbe. These studies assess the influence of compost addition on key soil properties, including structure, water retention and nutrient availability. In the case of the Mazingarbe site, particular attention was paid to the issue of contaminant transfer from soil to plants and the potential impact of reclamation measures on the spread of invasive species.

1.1. Analyses as part of broader research scope in the REECOL Project

Task 4.4 is closely linked to previous and parallel activities within the REECOL Project. In particular, it directly builds on results obtained under *WP3*, including the classification of soil degradation levels, characterization of study areas, and climate change adaptation scenarios. These data formed the basis for selecting test locations, designing experimental setups, and interpreting results. An important element was also the cooperation within *WP4*, especially the use of compost developed under *Task 4.3*, which was physically delivered to international partners to enable testing. Monitoring of the effects of activities carried out under *Task 4.4* is conducted using indicators and methods developed within *WP5*, ensuring methodological consistency and comparability of results across the entire project (Fig. 1).

The results presented in this report constitute a significant contribution to the subsequent stages of the REECOL Project, particularly in the context of developing guidelines and recommendations for post-mining land management. They demonstrate that industrial and energy crops can be the reclamation direction that fulfils environmental, climatic, and economic objectives, while simultaneously reducing contamination exposure in

degraded soils. Results also demonstrate that degraded soils can be rehabilitated with support of appropriately selected organic amendments.

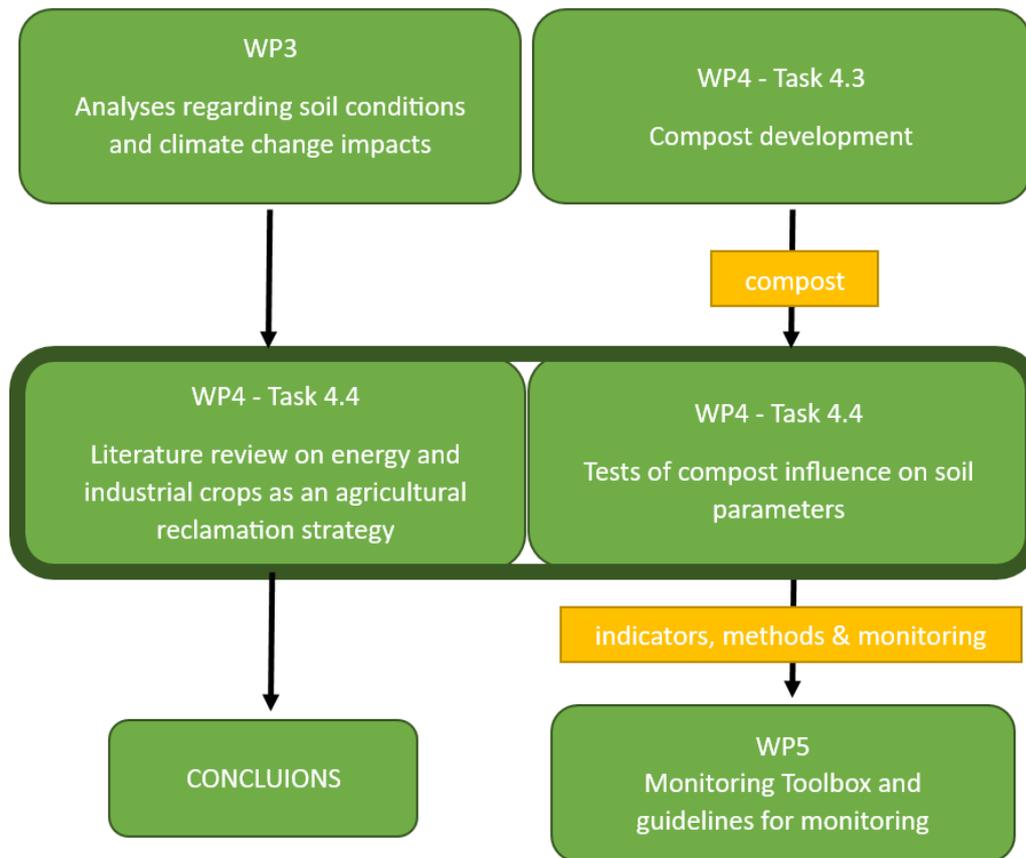


Fig. 1 Task 4.4 as part of a bigger picture in the *REECOL* Project.

1.2. Scope of the theoretical research (PART I)

The scope of the analyses and theoretical research conducted within *Task 4.4* was focused on assessing the feasibility, environmental relevance, and functional role of industrial and energy crops as a reclamation pathway for post-mining areas. The analytical framework combines a structured literature review with comparative spatial, soil, and process-based considerations derived from earlier project tasks and external scientific evidence.

The analyses address post-mining landscapes formed after coal extraction, with particular emphasis on large-scale open-pit lignite mines and their reclaimed or partially reclaimed surfaces. These areas are characterized by extensive spatial continuity, relatively gentle slopes, and engineered landforms, which fundamentally differentiate them from smaller, steeper hard-coal spoil heaps. The research therefore examines how geomorphological parameters - such as slope inclination, elevation variability, and topographic wetness patterns - condition the suitability of reclaimed land for large-scale agricultural use, including mechanized cultivation and biomass harvesting.

From a soil science perspective, the theoretical research covers key physical, chemical, and biological soil properties that determine the success or failure of industrial and energy crop cultivation on degraded substrates. Particular attention is given to soil structure, soil granulometry, bulk density, and water retention capacity, as water availability is identified as a primary limiting factor under both degraded soil conditions and future climate scenarios. Chemical aspects include pH, nutrient availability (including nitrogen, phosphorous and exchangeable cations), SOC (quantity and quality), soil inorganic carbon (SIC), and the behaviour of

potentially toxic elements, especially in the context of distinguishing food production from non-food biomass agricultural systems. Biological dimensions focus on microbial biomass and microbial enzymatic activity, as well as the potential for long-term soil function recovery.

A central element of the analytical scope is the role of industrial and energy crops in climate change mitigation and adaptation. The research examines their capacity for SOC sequestration, enhancement of soil organic matter (SOM) stocks, and resilience to drought conditions. Energy crops are assessed as potential long-term carbon sinks due to reduced soil disturbance, extensive root systems, and continuous biomass inputs to the soil. These aspects are evaluated in relation to land-use change considerations.

The theoretical framework further investigates the environmental trade-offs associated with different reclamation pathways. This includes the influence of vegetation cover on surface albedo, local microclimate, erosion control, and hydrological functioning, as well as the risks associated with intensive biomass production, such as nutrient depletion, soil compaction, and biological simplification under monoculture systems. These risks are explicitly addressed to avoid presenting energy crops as a universally optimal solution, emphasizing instead the importance of crop selection, spatial planning, and management practices.

An additional analytical dimension concerns the use of industrial and energy crops on contaminated soils. The scope includes a review of phytoremediation mechanisms - such as phytoextraction and phytostabilization - and their relevance for post-mining areas affected by heavy metals.

Finally, the theoretical analyses are applied in a site-oriented manner, with dedicated considerations for the Velenje post-mining area. These site-specific reflections do not constitute full feasibility studies but provide a conceptual assessment of how local geomorphology, soil properties, climate conditions, and land-use constraints influence the suitability of industrial and energy crops as a reclamation option. This approach ensures coherence between the theoretical research and the broader objectives of the *REECOL* Project.

PART I

2. Research on industrial and energy crops in the context of post-mining land degradation and soil dysfunctions

2.1. Characteristics of post-mining areas - spatial and geomorphological context

2.1.1. Typology of post-mining landscapes

Post-mining landscapes are examples of highly transformed anthropogenic systems, constituting one of the most striking examples degraded lands. Two main types of post-mining landscapes can be distinguished:

- Open-pit/opencast landscapes - characterized by extensive, gently sloping surfaces of external and internal dumping grounds, high spatial continuity, and significant hypsometric changes. Such areas dominate lignite mining (e.g., in Germany, Poland, Greece). The mining and dumping operations create final pits with gentle slopes, which are often transformed into post-mining lakes or agricultural land after mining ceases (Henselowsky et al., 2021); (Kuter, 2013).
- In contrast, waste heaps, typical of hard coal mining, are characterized by steeper slopes and a smaller area. Their limited stability and higher risk of erosion make them more difficult to convert into agricultural land, and reclamation efforts often focus on afforestation or natural landscape functions (Gerwin et al., 2023).

Geomorphological diversity is also important for future uses. Opencast areas can support the cultivation of energy crops, as well as industrial plants with high surface area requirements and high biomass, such as hemp (*Cannabis sativa L.*), flax (*Linum usitatissimum L.*), or kenaf (*Hibiscus cannabinus L.*). These species adapt well to the uniform, flat surfaces of dumping grounds, where fully mechanized cultivation and harvesting are possible. In hard coal heaps areas with steeper slopes and varied topography, plants with strong root systems, such as kenaf, castor bean (*Ricinus communis L.*), and camelina (*Camelina sativa L.*), also perform anti-erosion and stabilization functions, improving the soil structure and limiting its displacement (Struik et al., 2000; Amaducci et al., 2015).

The use of industrial and energy crop mixtures (e.g., hemp + miscanthus) enables the simultaneous achievement of reclamation and production goals, combining soil protection with the production of raw materials for the biomaterials and bioenergy industries.

Conclusion: the typology of post-mining landscapes provides a framework for selecting industrial and energy plant species. Opencast areas favour mechanized biomass production and large-scale cropping, while steeper slopes of dumping grounds require stabilizing plants. The integration of species with complementary functions - production and protection - provides the basis for sustainable agricultural and industrial reclamation systems.

2.1.2. The impact of terrain on agricultural use

Terrain shape is one of the key factors limiting or supporting agricultural activity in post-mining areas.

Literature analyses indicate that:

- **Slope angle** determines both the possibility of mechanization and the risk of erosion. Areas with a slope of $<5^\circ$ are considered most suitable for agriculture and energy crops (Servou et al., 2023).
- **Microrelief and relative altitude** shape water redistribution and microclimate, which is particularly important for plants with high water requirements, such as hemp and miscanthus (*miscanthus × giganteus*), which thrive in flat areas with good water retention (Chen et al., 2015). Flax and camelina, on the other hand, are more resistant to periodic drying and are recommended for gently sloping areas with moderate subsoil permeability, making them valuable species for the mosaic development of post-mining areas.
- **Topographic moisture indices** (e.g., Topographic Wetness Index - TWI) have a significant impact on organic carbon accumulation and the quality of anthropogenic soils, determining the development of both

energy crops and industrial plants with deep root systems, such as kenaf, which can improve infiltration and water accumulation in the soil profile (Kozłowski et al., 2025).

Different terrain also influences the direction of soil material redistribution and the dynamics of erosion processes, which should be taken into account when designing drainage systems and planning cropland networks. In a practical context, industrial plants with large root masses promote the biological consolidation of slopes and stabilization of waste heap surfaces, serving as an alternative or complement to typical energy species in landscape reclamation plans.

Conclusion: terrain topography directly determines the possibilities for reclamation and agricultural use of post-mining areas. Flat and gently sloping terrain favours productive industrial and energy biomass crops, while areas with greater hypsometric diversity require species with protective and stabilizing functions.

2.1.3. The importance of geomorphological parameters for crop mechanization and biomass harvesting

Geomorphological parameters - particularly slope and microrelief - influence the feasibility of mechanization and the efficiency of biomass harvesting. Areas of post-lignite opencast mines, with their gentle slopes, are favourable for mechanized cultivation of energy crops such as giant miscanthus (*miscanthus x giganteus*) and industrial hemp, which allow for harvesting using standard agricultural machinery (Prade et al., 2017).

Areas with more varied topography require precise field planning and terracing - especially in areas with internal dumping grounds, where subsidence and local soil compaction occur (Blachowski et al., 2023). Kenaf, hemp, and flax crops in such conditions serve both productive and reclamation purposes - the roots strengthen soil structure, and the biomass provides raw material for the production of technical fibers, biocomposites, and construction materials (Prade et al., 2017).

GIS and DEM analyses utilize methods to assess so called "agricultural space availability" - allowing for the determination of maximum allowable slopes for agricultural machinery and biomass transport routes (Servou et al., 2023).

The use of precise spatial models enables the identification of optimal zones for the production of industrial and energy crops in interdependent systems - for example, mosaic strips of hemp and miscanthus can increase the biodiversity and stability of the reclaimed ecosystem.

Conclusion: the geomorphological context of post-mining areas significantly determines their future use. Former lignite mine sites, with their gentle relief and high spatial continuity, are the most favourable locations for industrial and energy crops, while spoil heaps require complex stabilization solutions and mechanization constraints. Integrating geomorphological analyses with GIS tools and hydrological models is crucial for effective reclamation planning and sustainable use of these areas.

2.2. Properties of degraded soils and their impact on the success of energy/industrial crop cultivation

Reclaimed post mining soils have significant physical (compaction, low porosity), chemical (alkalinity, lack of SOC, nitrogen, phosphorus, potassium and other trace elements, potential heavy metal pollutants), and biological (low microbial biomass and enzymatic activity) limitations. However, appropriately designed reclamation treatments - nitrogen-fixing legumes, organic and mineral fertilization, and improving the physical structure - enable the restoration of their productive capacity and their use for energy and industrial crops, such as hemp or flax which are characterized by high adaptability to degraded soils and the ability to improve the physical structure of the soil. They contribute to soil organic matter accumulation primarily through extensive root systems, that remains in the soil after harvesting.

2.2.1. Physical properties of soils

The physical properties of post-mining soils largely determine their suitability for reclamation and the cultivation of energy crops. Soil structure (granulometry and compaction), bulk density, and water retention capacity are key factors. Reclaimed soils are characterized by improved bulk density (1.5-1.8 g/cm³) and low porosity, which limits root development and water infiltration (Feng et al., 2019).

For soil rehabilitation the perennial cultivation of legumes (legume family), such as alfalfa (*Medicago sativa* L.) is primarily used. It significantly improves soil structure by increasing total porosity and water capacity, as well as reducing bulk density by 7-11% (Otremba et al., 2020). Different vegetation types influence the distribution of physical parameters in the soil profile: grasses and herbs improve surface properties (0-10 cm), while trees increase water retention in deeper layers (10-20 cm) (Misebo et al., 2023).

Industrial crops can be used as well for soil rehabilitation. Industrial crops such as hemp and kenaf, thanks to their robust root systems, can significantly reduce soil bulk density and increase total porosity. Studies in post-mining regions in Italy and Spain showed that kenaf cultivation reduced soil bulk density by 0.12 g/cm³, and hemp increased water infiltration by over 20% after three growing seasons (Amaducci et al., 2015).

Flax and camelina, on the other hand, have shorter but dense root systems, which promote improved topsoil microstructure, increasing water capacity and reducing surface runoff (Keller et al., 2020). Water capacity indicators, such as capillary water capacity and soil water storage, are important for determining crop potential under drought conditions. Rehabilitation with herbaceous vegetation can increase soil water storage by 15-30% compared to degraded soils (Pinto et al., 2020), while the inclusion of industrial plants with extensive root systems - such as kenaf or hemp - further improves these parameters by up to 10-15%, indicating their high phytohydrological potential (Liu et al., 2023).

Conclusion: Improving the physical properties of degraded soils requires the introduction of vegetation with robust root systems (e.g., hemp, kenaf) combined with structural measures such as solid organic amendments and legumes, which increase SOM, promote aggregate formation, and thereby enhance soil porosity, profile stability, and long-term water retention.

2.2.2. Chemical properties

The chemical properties of post-mining soils are strongly dependent on the type of overburden and reclamation processes. Post-mining soils formed on lignite dumping grounds often have an alkaline pH (pH 7.5-8.2) and high CaCO₃ content, which limits the bioavailability of phosphorus and micronutrients (Otremba et al., 2020). This soil property also limits the bioavailability of metals in the soil and the soil-plant metal transfer (Perlein et al. 2021).

The use of NPK fertilization boosts plant productivity and indirectly increases the SOC content by 18-35%, total nitrogen by 10-18%, and sorption capacity by 25-43%, while also improving the mobility of phosphorus and potassium (Kaczmarek et al., 2023). However, high calcium carbonate content may promote the immobilization of heavy metals such as Cd and Zn, which reduces their bioavailability and hinders the micronutrient supply of energy crops (Spasić et al., 2024).

Industrial plants, particularly hemp and flax, have the ability to actively absorb and accumulate macro- and micronutrients from soils with low nutrient content. Hemp increases organic nitrogen and total SOC content by 10-20% after 3-4 growing seasons thanks to the intensive decomposition of root residues and mulch/litter (Linger et al., 2002).

Kenaf and castor bean, on the other hand, have the ability to accumulate phosphorus and potassium in biomass and improve the C:N balance in alkaline soils, facilitating organic matter mineralization processes. Camelina, as a species with low soil requirements, thrives in soils with elevated pH, and its post-harvest residues increase the availability of sulphur and potassium in the topsoil (Hossain, 2011).

For example, post-mining soils in the Konin area were characterized by high Mg and Ca content, creating favourable conditions for energy reclamation, provided that P and K are supplemented (Otremba et al., 2020).

Conclusion: rehabilitation of chemical parameters of post-mining soils requires balanced mineral and organic fertilization and the introduction of species with high adaptability (hemp, kenaf, camelina), which improve nutrient cycling and stabilize pH through active processes.

2.2.3. Biological properties

The biological functions of post-mining soils are typically - initially severely limited - but can be gradually restored through the introduction of vegetation, organic fertilizers, and soil microorganisms.

Microbiological activity increases even several times after the application of composts, which accelerate humification and increase enzymatic activity (Myszura-Dymek & Żukowska, 2023). Legumes and nitrophilous plants play a key role in the accumulation of nitrogen and organic matter, as well as in stimulating soil microbial activity (Pietrzykowski et al., 2018).

Industrial crops increase the population of rhizosphere bacteria and mycorrhizal fungi, supporting the formation of stable soil aggregates and improving soil structure (Bhattacharya et al., 2021).

Cultivation of fibre crops increases SOM content and the share of active organic matter can increase due to the root systems. The organic matter content of reclaimed soils increases over time - studies from the Czechia and Poland indicate that after 30-50 years, it can reach 50-70% of the value of natural soils (Spasić et al., 2021). The use of organic amendments (e.g., composts) accelerates the restoration of biological activity and stabilizes the soil system (Bharti et al., 2023).

Conclusion: restoring the biological functions of degraded lands requires the synergy of legumes, industrial plants, and energy plants, as well as microbial support. The combined action of roots, microorganisms, and organic matter rebuilds the soil cycle and improves long-term soil productivity.

2.3. The role of industrial and energy plants in mitigating and adapting to climate change

2.3.1. Potential for atmospheric CO₂ sequestration through soil organic carbon (SOC) accumulation

Rehabilitated post-mining soils, especially those originating from lignite open-pit operations, exhibit significant potential for atmospheric CO₂ sequestration through the accumulation of SOC. This process is primarily driven by the establishment of deep-rooted perennial crops - both energy and industrial - combined with the application of organic amendments that enhance soil aggregation and biological activity (Chimento et al., 2016; Blanco-Canqui, 2016).

Field studies have demonstrated that reclamation with sewage sludge and composted organic matter improves the stability of soil organic carbon pools, particularly the physically protected micro-aggregate fraction, which enhances long-term carbon retention (Kowalska et al., 2023; Ferrarini et al., 2022). In reclaimed lignite soils, the incorporation of carbon-rich residues leads to the accumulation of aromatic and acetyl carbon compounds, increasing the chemical recalcitrance of soil organic carbon and reducing its mineralization rate.

Research across Central Europe confirms that perennial bioenergy crops such as black locust (*Robinia pseudoacacia*), willow (*Salix sp.*), poplar (*Populus sp.*), miscanthus, or switchgrass (*Panicum virgatum L.*) can substantially increase soil organic carbon stocks in post-mining soils. After 6-11 years of cultivation, the mean soil organic carbon sequestration rates ranged between 0.4 and 1.1 Mg C ha⁻¹ yr⁻¹, depending on crop type and soil management (Martani et al., 2020; Don et al., 2012). Woody crops tend to sequester more carbon in stable fractions due to higher litter inputs, while herbaceous crops favour faster soil organic carbon turnover and improved microbial activity.

Industrial crops also demonstrate a significant capacity for carbon sequestration under reclamation conditions. Hemp, when cultivated on marginal or post-mining lands, can accumulate C through dense rooting systems and substantial belowground biomass, approaching the efficiency of leading energy crops such as miscanthus and switchgrass (Abreu et al., 2022; Malabadi et al., 2023). Similarly, kenaf and flax provide high carbon inputs to the soil due to their fibrous residues and potential for use in circular bioeconomy systems.

Recent advances highlight that biostimulants and mycorrhizal inoculation can further increase CO₂ sequestration efficiency in both hemp and miscanthus, enhancing photosynthetic carbon use and promoting root-derived soil organic carbon accumulation (Rostocki et al., 2024; Peroni et al., 2024). The integration of these biological tools with organic amendments and reduced tillage can transform post-mining areas into long-term carbon sinks, aligning with EU Soil Strategy and climate neutrality objectives.

Conclusion: post-mining soils, especially those rehabilitated using organic amendments and planted with plants with extensive root systems - both energy and industrial - can act as effective long-term carbon sinks.

2.3.2. Impact on Soil Organic Matter balance

SOM is a key component of the carbon balance, influencing both the fertility and stability of ecosystem functions. Long-term studies indicate that reclamation with biosolids increases soil organic matter content by 1.73 Mg C ha⁻¹ per year, and this effect persists for more than 20 years after application (Tian et al., 2009).

In post-mining soils, increased SOM content is associated with increased microbial activity and stabilization of the mineral-bound carbon fraction (Ruiz, 2023).

Industrial crops have a significant impact on the SOM balance. Hemp under remediation conditions can increase SOM thanks to the intensive supply of belowground biomass, especially in the 0-15 cm layer (Pagnani et al., 2018). Kenaf and camelina cultivation increase the active fraction of SOM and support microbial carbon stabilization in soil, as observed in remediation studies in the Mediterranean basin (Angelini et al., 2016). Flax and castor bean, thanks to the presence of abundant root biomass, improve the C:N ratio and increase the soil's capacity for long-term organic matter binding, which provides an additional remediation effect (Mukherjee et al., 2019).

Conclusion: Energy and industrial crops support SOM restoration through the constant supply of root biomass and mulch/litter, accelerating humification and soil carbon stabilization. Their inclusion in reclamation increases both the productivity and ecosystem sustainability of the restored areas.

2.3.3. Drought resistance and yield stability in degraded conditions

Energy crops demonstrate a high level of adaptation to water stress and soil degradation. Miscanthus × giganteus and Panicum virgatum maintain high productivity under limited moisture conditions thanks to their deep root systems and efficient transpiration, which simultaneously increases carbon accumulation in the root zone (Morris, 2025).

Research from Greece demonstrates that Robinia pseudoacacia cultivation not only sequesters carbon but also enriches the soil with nitrogen, increasing its drought resistance and improving nutrient cycling (Xanthopoulos et al., 2023).

Remediation using CO₂-fixing bacteria, improves the resistance of post-mining soils to water stress and supports plant growth in semi-arid conditions (Han et al., 2025). Industrial crops also demonstrate high resistance to abiotic stress. Hemp, flax, and camelina tolerate periodic water deficits well thanks to their efficient transpiration and ability to reduce water loss through leaves.

Conclusion: both energy crops and industrial crops demonstrate the ability to adapt to drought and degradation, contributing to the stabilization of reclaimed soil systems. The inclusion of species with diverse root architecture allows for better use of available water resources and improves the sustainability of biomass production.

2.3.4. Potential role as long-term carbon sinks

Post-mining lands reclaimed with energy crops can act as sustainable carbon sinks over the long term. Long-term analyses in Poland and the Czechia have shown that land reclaimed with the addition of organic amendments maintains a negative CO₂ emission balance, meaning that more CO₂ is captured than emitted (Kowalska et al., 2022).

Global analyses indicate that biosolids, biochar, and lignite materials are key tools for increasing the sustainability of carbon sequestration in soils for hundreds of years (Muhammad, 2019). Industrial crops such as hemp, kenaf, and castor bean can further enhance carbon sequestration potential through integration with bioenergy and bioindustrial systems.

Conclusion: combining biological reclamation with energy and industrial plants and the use of soil amendments (biochar, biosolids) can transform post-mining areas into sustainable carbon sinks. Such systems contribute to climate neutrality strategies while creating renewable raw materials with a low carbon footprint.

2.4. Environmental trade-offs and limitations of various reclamation pathways

2.4.1. Changes in surface albedo, microclimate, and water balance

Reclamation of post-mining areas using energy and industrial plants affects not only soil properties but also the surface energy balance, microclimate, and water circulation.

Changing land cover from exposed heap/dumping ground surfaces (albedo 0.25-0.35) to herbaceous and woody vegetation (albedo 0.15-0.20) leads to a lower albedo, which increases local heating but promotes moisture retention and evaporation during the diurnal cycle (Feng et al., 2019).

Studies in arid regions of China have found that covering surfaces with higher leaf area index improves soil moisture and the local microclimate, reducing surface temperature fluctuations by up to 4-6°C during the day (Aili et al., 2024). The impact on water balance depends on the terrain's morphology - reclaimed areas with varied microrelief favour infiltration, while homogeneous surfaces of lignite open pits exhibit a higher risk of surface runoff (Lechner et al., 2016).

Incorporating industrial and energy crops allows for a better balance of water balance - tall energy crops increase shading and evaporation, while shorter fibre crops reduce surface runoff, improving infiltration and microretention (Amaducci et al., 2015).

Conclusion: vegetation restoration improves water balance and microclimate, but requires planning the spatial structure of the vegetation cover, taking into account differences in albedo and transpiration between industrial and energy crops, to avoid local overheating and excessive surface runoff.

2.4.2. Erosion control and improved hydrological landscape functioning

Erosion control and hydrological stability are key criteria for assessing the effectiveness of rehabilitation. Rehabilitation using grass and shrub species reduces erosion by 30-50% by increasing root density and reducing surface runoff (Mensah, 2015). Hydrological models indicate that restored areas with diverse vegetation have better hydrological connectivity and lower water loss rates, reducing the risk of erosion even during heavy rainfall (Liu et al., 2023).

In Poland and Germany, micro-landscape strategies are being used to reduce erosion and improve infiltration by restoring natural microrelief and terracing slopes (Macdonald et al., 2015). Industrial plants play a particularly important anti-erosion role - thanks to their dense root systems (up to 2.5 m), hemp and kenaf stabilize the soil, reducing soil loss.

Flax and camelina strengthen topsoil layers and reduce erosion micro-cracks, improving water retention and reducing susceptibility to wind erosion. Castor bean (*Ricinus communis* L.), due to its strong taproot, is an effective stabilizing species on slopes above 10° (Mukherjee et al., 2019). The use of mosaic strips of energy crops (e.g., giant miscanthus, energy willow) with industrial crops (hemp, kenaf) enhances the hydrological structure of the landscape, combining infiltration with phytostabilization (Amaducci et al., 2015).

Conclusion: the use of multi-layered vegetation, including both energy and industrial crops, and micro-landforming techniques is an effective way to minimize erosion and improve hydrological functioning in post-mining areas.

2.4.3. Risks of intensive biomass production: nutrient depletion, soil compaction, biological simplification

Although energy crops are an important element of land reclamation and carbon management, they also pose significant environmental risks:

- Long-term monocultures (e.g., Miscanthus, Salix) lead to nutrient depletion and reduced nitrogen, phosphorus, and potassium content if not balanced with organic fertilization (Williams et al., 2020).
- Heavy equipment used for biomass harvesting causes soil compaction in technogenic soils, which reduces porosity and leads to reduced yields in subsequent cycles (Pambudi et al., 2023).
- Monocultures reduce biodiversity and ecosystem stability - the simplification of biological structure results in decreased microbiological activity and increased susceptibility to pathogens (Némethy & Szemethy, 2019). In commercial crops, these risks are similar, but can be mitigated through appropriate species selection and rotation systems. Cropping hemp, kenaf, or camelina in rotation with miscanthus or willow reduces the risk of soil depletion due to their different nutrient requirements and root structure (Linger et al., 2002; Amaducci et al., 2015).

Conclusion: to avoid secondary degradation, biomass reclamation in post-mining areas should be carried out in agroforestry and rotational systems, combining energy and industrial species, with soil compaction control and appropriate nutrient balancing.

2.4.4. The importance of spatial planning and species selection

The effectiveness and sustainability of rehabilitation depend on strategic spatial planning, integrated with local geomorphological and climatic conditions. Incorporating the Sustainable Development Goals (SDGs) approach into post-mining planning enables better integration of environmental and economic functions (Simpson et al., 2025).

The selection of species with high soil rehabilitation potential and nitrogen-fixing capacity enables the simultaneous restoration of ecological functions and soil stabilization (Pratiwi et al., 2025).

Spatial planning should also consider the mosaic landscape (forest, grassland, and energy zones), which allows for the balance of water retention, biodiversity, and biomass productivity (Bandyopadhyay & Maiti, 2022). Industrial crops should be an integral element of land reclamation planning - their shorter cultivation cycles and high biomass allow for flexible spatial management. Hemp and kenaf can act as buffer zones between energy crops and areas of natural succession, reducing erosion and improving infiltration (Angelini et al., 2016). Flax and camelina can be planted in areas with poorer water conditions, creating systems that improve microretention and prevent surface overheating. The inclusion of industrial crops increases the flexibility of landscape planning and supports the economic use of biomass.

Conclusion: effective land reclamation planning requires a landscape approach and the integration of industrial and energy crops into mosaic spatial arrangements, ensuring a balance between production, ecological, and social functions.

2.5. Phytoremediation potential of industrial and energy plants in polluted areas

2.5.1. Phytoremediation mechanisms for heavy metals and inorganic compounds: phytoextraction, phytostabilization

Phytoremediation encompasses a set of biological processes that utilize plants to remove, stabilize, or neutralize heavy metals and inorganic compounds in soil (Falconi et al., 2025).

Key mechanisms include phytoextraction (uptake and accumulation of contaminants in above-ground biomass) and phytostabilization (immobilization of metals in the root zone and reduction of their mobility). Both processes are supported by rhizosphere microorganisms and organic and inorganic additives (Randelović et al., 2025; Priya et al., 2023). They can aid the plant to maintain or reduce the contaminant mobility in the soil

and the transfer in the plant which is the goal in a phytostabilization strategy. On the contrary, the reverse action is expected in a phytoextraction strategy, i.e. increase the contaminant mobility in the soil and the transfer in the plant. Phytostabilization requires contaminant excluder plant whereas phytoextraction requires contaminant (hyper)accumulators (Falconi et al., 2025).

Industrial and energy crops exhibit both phytoextraction and phytostabilization mechanisms. Heigh of the ten industrial crops: sorgho (*Sorghum sp.*), flax, gum tree (*Eucalyptus sp.*), willow, beet root (*Beta vulgaris L.*), purple tansy (*Phacelia tanacetifolia Benth.*), common mallow (*Malva sylvestris L.*), coriander (*Coriandrum sativum Linn.*) and wild spinach (*Chenopodium album L.*) grown on a metal-contaminated soil showed an excluder behavior that fits with low metal transfer in the harvested parts and then phytostabilization (Perlein et al., 2023, 2021b). As expected, the tested willows exhibited a Cd and Zn accumulating behavior in leaves which better fits with phytoextraction of these metals. The fast growing trees willows and poplars are indeed well known to accumulate Cd and Zn in their leaves, even if the level of these metals' accumulation varies according to the cultivar and soil properties. Cd being the most worrying metal for soil remediation and mobility, efforts were made to increase or decrease Cd aerial part concentration in metal accumulating plants such as coriander, poplar and willow to be used either in a phytoextraction or phytostabilization strategy, respectively. Inoculation with mycorrhiza or addition of organic (compost, biochar) or inorganic additives (NPK fertilizer) are useful tools for these aims (Perlein et al., 2021b, Phanthavongsa et al. 2017, Grignet et al., 2020). In addition, such input in combination with plants can bring other benefits like increase of OM and water retention, soil structure and plant health improvement, and plant biomass production (Ciadamidaro et al. 2017; Rosas-Ramírez et al., 2024; Bert et al. 2012). The coverage of the contaminated soil by the plants is required in both strategies to avoid contamination soil particles erosion by wind and water runoff. Relevant plant candidates are thus preferably perennial plants and those with a vertical and horizontal large root system (Falconi et al., 2025). Kenaf and castor bean are particularly effective in phytostabilizing Cd, Cr, and As in the root zone - their large-surface adsorption root systems enhance metal immobilization and improve soil structure. Intercropping with herbaceous plants can help phytoextraction to cover the soil when industrial fast growing tree are used (Grignet et al., 2020).

Conclusion: industrial and energy plants, thanks to their properties (extensive root systems and foliage soil cover, tolerance to soil contaminants and pedo-climatic conditions and rapid biomass growth), are an effective component of phytostabilization and phytoextraction systems, especially when combined with mineral or biological soil additives. Industrial and energy plants should fit into the landscape and bring economical gain in addition to the remedial and ecological benefits.

2.5.2. Impact on the removal of heavy metals and inorganic compounds

Energy plants, thanks to their large biomass and extensive root systems, are effective in removing heavy metals from post-mining soils. Species such as *Miscanthus × giganteus* and *Arundo donax* efficiently accumulate Zn, Cr, and Pb (up to 900 mg Zn·kg⁻¹ and 600 mg Cr·kg⁻¹) while limiting their leaching into groundwater (Fernando et al., 2018).

Willows are well studied for Cd and Zn phytoextraction as they accumulate these metals. The combination of willow (*S. viminalis*) and the Zn and Cd hyperaccumulating plant, *Arabidopsis halleri*, used as an intercropping and cover plant, to halve soil Cd and Zn concentrations allowed a reduction in the cleanup time to 36 years for Cd and 24 years for Zn (Grignet et al., 2020). Willows on this metal contaminated site for more than 8 years continuously grew and produced biomass yield equal to the one obtained on uncontaminated soil (58T/ha) suggesting that the trees were not impacted by the pollution and were adapted to the site conditions (Grignet, 2021). Two sorgho cultivars grew on a contaminated site for their phytostabilization potential showed tolerance to high levels of metal pollution similar with yields similar to that obtained on uncontaminated sites (Perlein et al. 2021c). In this study, attention has been paid to climate change and occurrence of increased temperature and drought events on sorgho growth. Sorgho appeared as a relevant alternative to crop cultivars such as maize in the region where the study took place (Haut-de-France region).

Conclusion: agricultural and forestry systems involving energy and industrial plants increase the efficiency of phytoextraction and phytostabilization of heavy metals while maintaining high biomass productivity. Crop selection should be made according to climate change anticipation.

2.5.3. Management of biomass from metal contaminated post-mining areas

Sustainable approaches integrate phytomanagement with energy and material production, allowing for the combination of soil remediation, emission reduction, and the use of the produced biomass on contaminated post-mining areas in industrial and agricultural systems (Randelović et al., 2025; Hegedus et al., 2023).

Management of biomass which does not contain metals is easiest compared to the one that contains metals. Industrial and energy crops exhibit an excluder behaviour, i.e. they don't have metals in their above ground parts which are harvested for processing. They can enter all types of processes without any specifications regarding contamination, only those related to the process itself. These crops suited for phytostabilization can be aided by soil amendments to improve their overall performances. Align with the circular economy principles, ten industrial non-food crops (*sorgho*, *flax*., *Eucalyptus*, *willow (Salix sp.)*, beet root (*Beta vulgaris* L.), purple tansy (*Phacelia tanacetifolia* Benth.), common mallow (*Malva sylvestris* L.), coriander (*Coriandrum sativum* Linn.) and wild spinach (*Chenopodium album* L.) grown on a metal-contaminated site were studied for adequacy in biogas, bioethanol, compost, natural dye, ecocatalyst, essential oil and fiber production processes (Perlein et al. 2023; Perlein et al. 2021 a, b, c). Each crop was assessed through their plant behavior on the metal-contaminated soil, agricultural parameters, plant characteristics for non-food processing, and regulation. Except for willows, all crops were excluders which fitted well with phytostabilization and further valorization. Indeed, all crops could be processed in one or several non-food biomass processing options without any metal constraint or after a pretreatment to remove Cd.

In contrast, appropriate management of biomass containing heavy metals is crucial to avoiding secondary emissions. Numerous studies were performed to check the feasibility of using such biomass in various energy and material production chains (Randelović et al., 2025). A literature review indicates that thermochemical processes (e.g. pyrolysis) can effectively concentrate metals in solid biochar, with pyrolysis providing the highest energy recovery and reducing atmospheric emissions (Dastyar et al., 2019). Some studies have shown that biochar from metal-enriched biomass can be reused to stabilize soils, creating a closed-loop remediation system (Boros-Lajszner et al., 2025). Some others have shown that biochar from metal-enriched poplar could not be used in agriculture (Bert et al. 2017). Not all sorgho cultivars grown on a metal-contaminated site fit for bioethanol and biogas production (Perlein et al. 2021) whereas willow and poplar need pretreatment to remove metals before processing (Ziegler-Devin et al. 2019; Asad et al. 2017).

Caution was raised concerning the competition with the spontaneous plant species which can raise from the soil or the surroundings to maintain the energy and industrial crops on post-mining areas (Perlein et al. 2023). Commercial biochar products resulting from pyrolysis of industrial biomass (from not contaminated sites) can be used for remediation as a metal sorbent and soil-structuring amendment (Muzammal et al. 2023). In any case, regulation and standard specification compliance at local, regional or national level should be verified to ensure the feasibility of using such energy and industrial crops to avoid metal unwanted emissions.

Conclusion: once the metal transfer in the process chain is controlled, biomass from contaminated post-mining areas should be directed to energy and material processing. Incorporating industrial plants into phytoremediation systems enables a closed-loop system of matter - soil remediation, energy recovery, and reuse of remediation products.

2.6. Summary of literature review

The transformation of post-mining areas in Europe represents a critical environmental and socio-economic challenge, but also a unique opportunity to create multifunctional, climate-resilient landscapes. The literature review conducted within *Task 4.4* of the REECOL Project demonstrates that the integration of industrial and energy crops into reclamation systems can effectively combine ecological restoration, biomass production, and carbon management objectives.

The analyses show that geomorphological diversity strongly determines the reclamation potential of post-mining land. Flat lignite opencast areas offer favourable conditions for mechanized cultivation of large-scale biomass crops, while steep, heterogeneous spoil heaps require species with stabilizing and phytoremediating functions. Industrial plants such as hemp, sorgho, flax, kenaf, and castor bean, together with energy crops like miscanthus, willow, and black locust, form complementary systems that enhance both soil productivity and ecological resilience.

From a soil perspective, reclaimed post-mining substrates are characterized by high bulk density, low porosity, nutrient imbalance, and limited biological activity. However, the introduction of deep-rooted perennial vegetation, legumes, and organic amendments markedly improves physical structure, increases water infiltration and retention, and stimulates microbial activity. Industrial crops demonstrate strong adaptability to these degraded conditions, enhancing the cycling of nutrients, organic matter accumulation, and soil carbon stabilization.

The climatic relevance of these systems is evident. Both industrial and energy crops contribute significantly to atmospheric CO₂ sequestration through soil organic carbon accumulation. The combination of organic amendments, microbial inoculation (i.e. selection of bacteria and mycorrhizae beneficial to plants and to soil function), and low-disturbance cultivation can transform reclaimed soils into long-term carbon sinks, aligning with the EU Soil Strategy for 2030 and climate neutrality targets.

At the same time, industrial and energy crops play a vital role in phytoremediation, particularly through phytostabilization mechanisms that reduce heavy metal mobility and improve soil quality. Their non-food nature minimizes the risk of contaminant transfer to the food chain, allowing the safe use of biomass for energy and industrial purposes. When properly managed, metal enriched biomass from phytoextraction can be processed thermochemically - through e.g. pyrolysis or gasification - to recover energy and produce biochar for reuse in soil stabilization, closing the reclamation and energy loops.

Nevertheless, reclamation through biomass systems is not free from environmental trade-offs. Monocultures may cause nutrient depletion, soil compaction, and biological simplification, while excessive water loss or local overheating can occur if vegetation structure is not spatially balanced. Therefore, spatial planning, crop rotation, and landscape-level design are essential to ensure functional diversity, erosion control, and hydrological balance.

3. Case study context and reference to selected research area

3.1. Theoretical possibilities of reclamation towards fast growing trees and energy and industrial crops in the Velenje post-mining areas (Slovenia)

Recently, the use of renewable energy sources has become increasingly important. Slovenia has been set a target within the framework of EU objectives and Fit-for-55 to reach at least 33% RES in final energy consumption by 2030.

Wood is one of Slovenia's most valuable natural resources because the country is heavily forested. Slovenia is among the most forest-rich EU members, and its forests form a key part of its bioeconomy, rural development, and renewable material supply. This strong natural endowment gives Slovenia a strategic advantage in using wood for construction, energy, and sustainable products. In this context, Slovenia's naturally rich forests fit into a broader European landscape where wood plays an important role in climate policy, renewable materials, and sustainable economic development. Because forests represent a major national resource, the Slovenian Government prepared the Strategy for the Wise Use of Wood Biomass for Energy to ensure that wood biomass is used sustainably, efficiently, and in line with circular bioeconomy principles. The strategy for the smart use of wood biomass for energy purposes was prepared by an interdepartmental working group from the Ministry of the Environment and Spatial Planning, the Ministry of Agriculture, Forestry and Food, the Ministry of Infrastructure, the Slovenian Forest Service, and the Forestry Institute. The main objectives of the development and implementation of this strategy are:

1. to discourage the use of high-quality wood for energy purposes,
2. to promote the smart and efficient use of lower-quality wood (which is no longer suitable for higher value-added products in the wood industry) for energy purposes,
3. to improve air quality in areas with exceedances and to maintain air quality in other areas of the country due to the use of wood for heating buildings,
4. supporting all smart management processes - managing Slovenian forests in the given circumstances, including the increasingly negative effects of climate change on Slovenian forests.

The strategy envisages a strong bioeconomy based primarily on the timber industry and renewable energy sources. Managing the impact of climate change on forests and society as a whole on the one hand, and the unfavourable ownership structure of forests, inefficient use of wood fuels in households, a lack of entrepreneurial initiative, and strong competition from neighbouring markets on the other, are challenges that require a comprehensive approach and the search for synergies between sectors. This approach is introduced by the Strategy for the Intelligent Use of Wood Biomass for Energy Purposes, as it envisages close cooperation between environmental protection, forestry, woodworking, and energy sectors. During the implementation of the strategy, emphasis will be placed on the effects of climate change, which are likely to affect the structure and condition of Slovenian forests. These effects primarily include natural disasters, the emergence of new and the spread of existing natural pests, and changes in microclimatic growing conditions (extreme temperatures, droughts, etc.). It is necessary to adapt the use of wood to these influences and to establish mechanisms that will ensure optimal harvesting, processing, and use of wood under such conditions. Slovenia strategy is envisaging to primary use more existing resources as it has 60% of its land covered by forest which is sufficient natural resources. Strategies promote better use of existing forests, not the expansion of monocultural plantations. Despite that primary strategic goals there are other purposes to properly rehabilitate and reclaim degraded and polluted areas due to coal mining effects. In that sense strategy emphasis is placed on biodiversity and sustainability.

Wood fuels include lower-quality forest wood assortments; logging residues from forest thinning; residues from wood processing; wood from agricultural areas; wood residues from the maintenance of roads, parks, meadows, and tree-lined avenues; and discarded wood that has not been chemically treated. One of the options for utilizing wood biomass is therefore, in addition to natural forests, non-forest plantations of fast-growing species, where poplar and willow clones are mostly used.

3.1.1. Previous studies considered

Research into non-forest plantations began in the 1960s (Steinbeck, 1999). Technologies and clones suitable for non-forest plantations were developed in Scandinavia, Italy, and Central Europe. Originally, the main purpose of these plantations was to provide wood for the pulp industry, but today wood from these plantations has become an important source of energy.

Out-of-forest plantations of fast-growing tree species are characterized by high quantitative yield, high density of seedlings, and clump growth (except in the first rotation). The life span of a plantation is the period from its establishment to the end of its exploitation. In plantations of fast-growing tree species, this period can last up to 30 years before complete regeneration becomes necessary, depending on the tree species selected and individual clones (Defra, 2002).

The impacts of this type of farming can be divided into four different groups:

- impacts on biodiversity,
- impacts on the landscape, and
- effects on soil properties and hydrological conditions.

To minimize the impact on the landscape the plantations should be as finely structured as possible, that neighbouring plantations should not be harvested in the same year, that larger areas should be harvested over several years by dividing them into smaller areas, and that plantations should consist of a mixture of several different tree species or clones. The impact of cultivated plantations on soil properties is similar to that of agriculture, meaning that the soil needs to be fertilized, irrigated in dry areas, weeded, etc.

Suitable locations for fast-growing tree species plantations (also so called short rotation forestry) in context of mining areas are abandoned agricultural land, agricultural land with less favourable conditions for food and feed production, contaminated areas (e.g. where power plant fly ash is installed), locations near railways and roads, and steep areas where agricultural cultivation may lead to increased erosion risk. All these areas are affected by coal mining and other coal related industrial activities.

Main characteristics of such plantations are a large yield of biomass, high planting density and growth of coppice. Growing time, i.e. the period between harvests on these plantations, generally varies between 2 to 5 years, perhaps even longer periods. Planting of cuttings can be done in single or double rows..

The amount of wood mass produced per hectare depends on the tree species, the length of the rotation period, soil quality, and the intensity of care. On favourable land, poplars can yield a higher return than willows. The amount of wood mass produced is usually given in tons of dry matter (absolute dry wood - atro). In less favourable growing conditions, this should amount to 7-9 t atro/ha/a for poplar and willow, in favourable growing conditions 10-15 t atro/ha/a for poplar and 10-14 t atro/ha/a for willow, while in optimal growing conditions we can expect 16-25 t atro/ha/a for poplar and 15-20 t atro/ha/a for willow. Many authors cite very different estimates of dry matter yields which indicated that this is very much site specific. E.g. plantations can be affected by unexpected external factors related to weather conditions, pests, and grass and weed growth.

In Slovenia there are currently two test plantations of fast-growing tree species on coal mining areas. One is in Velenje and one in Trbovlje. Trbovlje is former coal mine which stopped with coal production in 2014. The first plantation was planted by Premogovnik Velenje (PV) where tree growth has proven successful. The second test plantation was established by Rudnik Trbovlje-Hrastnik, which planted a plantation of fast-growing willow trees on degraded mining areas in 2009. The growth of trees from this plantation has proven to be poor, but with a high survival rate (Božič, 2009). Velenje plantation shows better growth and was planned as a commercial plantation, not just a plantation for the revitalization of degraded areas.

3.1.2. PV case

As mentioned, PV has some experience with experimental planting of so called fast growing plants for energy purpose use as also with wood processing. In the location of the production coal mining area operating PV subsidy company PLP exist. It is wood processing plant, assuring different wood products for the coal mine

needs. Wood biomass is therefore important also in scope of fair transition and in light of possibilities of wood processing expansion after coal mine is closed.

The test plantation of fast-growing willow trees is located in the municipality of Velenje on the coal mining area. The plantation was established in April 2009 by Premogovnik Velenje on agricultural land where the soil was subsiding in the past due to the influence of the mine. The entire plantation covers 4.2 ha and consists of willow trees, clones Inger (*Salix triandra* x *S. viminalis*) and Tordis (*Salix schwerinii* x *S. viminalis* x *S. vim*), and to a lesser extent trees of various poplar clones for research purposes. The Inger clone covers 1.2 ha and the Tordis clone 2.2 ha. Subsequently, the Forestry Institute in cooperation with PV group planted various poplar clones on a 0.8 ha test area. Plantation lies at an altitude of 430 m, with a slope of 10%, an eastern exposure, and loamy soil with a distinct horizon. The trees are planted in double rows, with the spacing between individual cuttings in a row being 0.75 m. The spacing between individual cuttings within a row is 0.41 m, while the road width, i.e., the distance between the double rows, averages 3.12 m. With such an arrangement of cuttings, the planting density is 10,734 plants/ha.

Willow and poplar trees are undemanding in terms of soil quality, but they require sufficient rainfall and soil moisture, as well as a good supply of groundwater. If there is no rainfall during the period when the shoots are growing and the tree is most sensitive (until mid-May) (root length 5 to 10 cm), irrigation is necessary. In addition to the above, sufficient soil aeration is also necessary for good tree growth. If this is not achieved, the soil needs to be further cultivated. If the soil does not have enough humus or is not aerated enough or has a low level of nitrogen mineralisation, it needs to be additionally fertilised with nitrogen (Krajnc et al., 2009).

Harvesting is most suitable during winter dormancy, as most of the nutrients from the above-ground part are transferred to the root system, ensuring lush growth from the hives at the beginning of the new production cycle. As we know, winter harvesting is suitable because of less damage to the soil due to mechanization. Soil compaction due to the management of fast-growing plantations is not critical, as the use of machinery is minimal and can also be limited to a certain extent to times when the soil is less sensitive. Therefore, the plantation was cut in December 2009 to promote coppice growth.

The aim was to monitor the test plantation of fast-growing tree species. With the measurements carried out on selected plantation, the production potential of two different clones (*Salix* sp., clone Tordis and clone Inger) as an alternative energy source was determined.

Altogether, the measurements were performed three years in a row. The plantation has been monitored since its establishment for few years. A time study of planting operations was carried out during the tree planting phase, followed by periodic annual growth measurements in autumn. The plantation was measured in October 2009, September 2010, and September 2011.

Analysis of the situation on the Velenje plantation showed that the conditions for the growth of willow trees (Tordis and Inger) were suitable. During the first (2010) and second (2011) years of coppice growth, the average height of shoots was increased by 117% for clone Tordis and 113% for clone Inger, suggesting a comparable increment of both clones. Average volume of the coppice (clone Tordis) increased from 217.2 cm³ to 1164.7 cm³ between 2010 and 2011 and from 201.7 cm³ to 1063.8 cm³ for clone Inger. Growing stocks of Inger and Tordis clones in the second year of coppice growth (2011) were 7.98 m³/ha and 10.57 m³/ha, respectively. The increment between the first and second year of coppice growth of Inger and Tordis clones were 6.40m³/ha and 8.54m³/ha, respectively. The amount of biomass yield produced in the second year of coppice growth was 4.58 t atro/ha (Tordis) and 3.49 t atro/ha (Inger), indicating an improvement of biomass yield compared to the previous year. The main reason for the lower total yield of wood biomass for clone Inger lay in smaller diameters and, consequently, volume. Conclusion is that conditions for such planting are very good.

Since pilot tests, PV is not any more monitoring and analysing plantation. More detailed results since test are not available. Since then plantation was harvested in period of 3-4 years. Last harvest was done end 2024, when weather was colder and plants regarding humidity were of better quality. Harvesting was done in few days where manually chain saw and supplement farming machines were used. Yield was cca 960 m³ of biomass and costs of harvesting were cca 4.000,00 EUR. For more information more accurate and

methodological actions would be needed as re-measure the plantation before harvesting, to monitor harvesting of the plantation and production of wood chips and final calculation of biomass yield in the first growing period.

3.1.3. Prospects for fast-growing trees in PV mining area

Within the mining concession area of the Velenje Coal Mine, there is a significant extent of mining and former mining land that is, from a technical and environmental perspective, suitable for energy-related land uses, particularly for the cultivation of fast-growing plant species intended for biomass production. These areas currently include land used for agricultural purposes as well as subsidence areas formed because of underground mining activities. Due to their characteristics, such surfaces represent a considerable potential for development into designated energy locations based on biomass production. The cultivation of fast-growing biomass crops on mining and post-mining land offers several advantages. It enables the productive reuse of degraded or structurally altered land, contributes to the diversification of renewable energy sources, and supports the gradual transition of the region towards a low-carbon economy. In addition, biomass production can play a complementary role in land reclamation processes by improving soil structure, stabilising surfaces, and enhancing landscape integration over time. In addition, there is positive impact on soil (reducing the risk of landslides, erosion, and soil leaching) and on hydrological conditions. Plantations have a high capacity for interception, retaining large amounts of water in the soil, reducing evaporation (the ability to dry out waterlogged soil), reducing surface heating of the soil and, consequently, the evaporation of capillary water. In that context we have to consider that precipitation and evaporation are fundamental for monitoring the water balance of the subsidence remediation area. Evaporation values, together with precipitation, temperatures, and other meteorological parameters, indicate local climatic conditions, climatic fluctuations, and microclimate. There is limitation as due to biomass high water content, wood can only be used directly for energy in larger energy facilities (heating plants and power plants) which is in case of PV and Šaleška valley appropriate as power plant is assuring remote heating of cities and planning to renew existing system to new sources in the future. Otherwise, for commercial use, additional drying is required. As a recommendation, the average transport distance should not exceed 15 km. There is also usually high initial investment, where incomes came only after several years.



Fig. 2 Mining area and its subsidence influence zone, highlighting technically feasible areas (green) for the cultivation of fast-growing energy crops as a biomass resource.

Spatial planning in the mining area of the Velenje Coal Mine is further influenced by the national and regional coal region restructuring framework and the associated development projects. These initiatives pursue economic diversification, job creation, environmental rehabilitation, and improved quality of life, and they also place specific demands on land availability within the former mining landscape. As a result, the introduction of

biomass cultivation must be carefully coordinated with other planned or potential land uses, such as industrial redevelopment, renewable energy installations, nature conservation, recreation, and urban development.

When identifying and designating potential energy locations within the mining area, it is essential to consider the interests of landowners and current land users, as well as the expectations and development objectives of local communities. These interests are closely linked to spatial planning policies and the long-term vision for land use in the wider area. Transparent stakeholder engagement and participatory planning processes are therefore crucial to ensure social acceptance and balanced decision-making. In addition, we have to divide flat area and slopes where appropriate flat area has max 5-7 degrees. In that sense we have to consider that full mechanization of work is only possible on land with a slope of less than 15%. Also the forecasted subsidies should be fully considered.

Additional, planting on potentially polluted areas can also have environment benefits. PV is installing so called stabilizat (contains % of power plant fly ash) in to the remediation and recultivation area for land stabilization and recultivation purposes. Based on the previous results of soil and stabilizat analyses which is installed in majority in the recultivation area it between lakes, where may be potentially hazardous inorganic substances mainly represented by the elements As and Mo. There is also desire to lower Mn for which is no legal limit value but it influence on waters.

In this context, the use of mining and post-mining land for fast-growing biomass crops should be understood as a flexible, transitional and environment sustainable land-use option. It can serve both as a long-term energy solution and as an interim use that preserves land value, supports regional energy systems, and remains compatible with future spatial development scenarios. Properly integrated into spatial planning documents and restructuring strategies, biomass cultivation can thus contribute to a coherent, sustainable, and socially acceptable transformation of the mining area.

In Slovenia, wood biomass production from short rotation forestry is relatively unexplored. Slovenia can exploit this competitive advantage to make the transition to a low-carbon society more effective. The pillars of this transition are the processing of wood into various products and the efficient use of wood for energy purposes. These are synergistic effects that lead to a common goal: reducing greenhouse gas emissions, improving air quality, achieving energy independence, and creating a successful bioeconomy.



Fig. 3 Area with cultivation of fast growing trees in Velenje.



Fig. 4 Energy willow (PV photo collection).



Fig. 5 Fast growing trees (PV photo collection).

REFERENCES:

- Department for environment, food and rural affairs (DEFRA). 2002. Growing short rotation coppice: best practice guidelines for applicants to DEFRA's energy crops scheme. London, Department for Environment, Food & Rural Affairs.
- A new strategy for a sustainable Europe: The circular bioeconomy. WoodPoP <https://www.gov.si/novice/2025-04-08-nova-strategija-za-trajnostno-evropo-lesno-krožno-biogospodarstvo/>
- The strategy for the smart use of wood biomass for energy purposes. www.gov.si. 2024
- Zbornik gozdarstva in lesarstva 97 (2012), s. 19 -29, Tina ČEBUL, Wood biomass from outside forest plantations of fast-growing species
- Bozic G. 2009. Willows grow poorly on poor soil: renewable energy sources. Delo, 51, 274: 13Defra, 2002
- Krajnc N., Piskur M., Dolensek M., Bozic G., Klun J. 2009. Outdoor plantations of fast-growing tree and shrub species. Ljubljana, Gozdarski inštitut Slovenije, Zalozba Silva Slovenica: 15 str.
- Ministry of Agriculture, Forestry and Food . Operational program for the implementation of the National Forest Program 2022–2026, . October 2022
- Premogovnik Velenje. Internal material. 2025
- Steinbeck K. 1999. Thirty years of short-rotation hardwoods research. J.D. Haywood (Ed.), Proceedings of the Tenth Biennial Southern Silviculture Research Conference, USDA Forest Service, Asheville, NC (1999): 63–65 str.
- Bharti, B., Rana, M., Gautam, B., Negi, N., Mohan, J., & Arya, R. (2023). Organic Amendments for Soil Reclamation: A Review. *International Journal of Environment and Climate Change*. <https://doi.org/10.9734/ijecc/2023/v13i113586>
- Spasić, M., Borůvka, L., Vacek, O., Drábek, O., & Tejnecký, V. (2021). Pedogenesis problems on reclaimed coal mining sites. *Soil and Water Research*, 16, 137-150. <https://doi.org/10.17221/163/2020-swr>
- Pietrzykowski, M., Woś, B., Chodak, M., Sroka, K., Pająk, M., Wanic, T., & Krzaklewski, W. (2018). EFFECTS OF ALDERS (ALNUS SP.) USED FOR RECLAMATION OF LIGNITE COMBUSTION WASTES. *Journal American Society of Mining and Reclamation*. <https://doi.org/10.21000/jasmr18010030>
- Myszura-Dymek, M., & Żukowska, G. (2023). The Influence of Sewage Sludge Composts on the Enzymatic Activity of Reclaimed Post-Mining Soil. *Sustainability*. <https://doi.org/10.3390/su15064749>
- Otremba, K., Kozłowski, M., Tatuško-Krygier, N., Pająk, M., Kołodziej, B., & Bryk, M. (2020). Impact of alfalfa and NPK fertilization in agricultural reclamation on the transformation of Technosols in an area following lignite mining. *Land Degradation & Development*, 32, 1179 - 1191. <https://doi.org/10.1002/ldr.3781>
- Spasić, M., Borůvka, L., Vacek, O., Drábek, O., & Tejnecký, V. (2021). Pedogenesis problems on reclaimed coal mining sites. *Soil and Water Research*, 16, 137-150. <https://doi.org/10.17221/163/2020-swr>
- Kaczmarek, Z., Gajewski, P., & Zawieja, B. (2023). Impact of NPK fertilization in agricultural reclamation on the transformation of Technosols in post mining area: a case study from the Konin open-pit brown coal mine, central Poland. *Soil Science Annual*. <https://doi.org/10.37501/soilsa/176683>
- Liu, H., Wu, C., Yu, Y., Zhao, W., Liu, J., Yu, H., Zhuang, Y., & Yetemen, O. (2023). Effect of Solar Farms on Soil Erosion in Hilly Environments: A Modeling Study From the Perspective of Hydrological Connectivity. *Water Resources Research*, 59. <https://doi.org/10.1029/2023wr035067>
- Pinto, L., Stumpf, L., Miguel, P., D., L., Leidemer, J., Da Silva Barbosa, L., & Oliveira, M. (2020). Reclamation of Soils Degraded by Surface Coal Mining. . <https://doi.org/10.5772/intechopen.93432>
- Misebo, A., Szostak, M., Sierka, E., Pietrzykowski, M., & Woś, B. (2023). The interactive effect of reclamation scenario and vegetation types on physical parameters of soils developed on carboniferous mine spoil heap. *Land Degradation & Development*, 34, 3593 - 3605. <https://doi.org/10.1002/ldr.4705>
- Otremba, K., Kozłowski, M., Tatuško-Krygier, N., Pająk, M., Kołodziej, B., & Bryk, M. (2020). Impact of alfalfa and NPK fertilization in agricultural reclamation on the transformation of Technosols in an area following lignite mining. *Land Degradation & Development*, 32, 1179 - 1191. <https://doi.org/10.1002/ldr.3781>
- Feng, Y., Wang, J., Bai, Z., & Reading, L. (2019). Effects of surface coal mining and land reclamation on soil properties: A review. *Earth-Science Reviews*. <https://doi.org/10.1016/j.earscirev.2019.02.015>

- Kozłowski, M., Otremba, K., Pająk, M., & Pietrzykowski, M. (2025). Effect of topography and properties of parent materials on organic carbon content in technosols of a post-mining lignite site. *Scientific Reports*, 15. <https://doi.org/10.1038/s41598-025-19131-2>
- Chen, J., Li, K., Chang, K., Sofia, G., & Tarolli, P. (2015). Open-pit mining geomorphic feature characterisation. *Int. J. Appl. Earth Obs. Geoinformation*, 42, 76-86. <https://doi.org/10.1016/j.jag.2015.05.001>
- Servou, A., Paraskevis, N., Roumpos, C., & Pavloudakis, F. (2023). A Geospatial Analysis Model for the Selection of Post-Mining Land Uses in Surface Lignite Mines: Application in the Ptolemais Mines, Greece. *Sustainability*. <https://doi.org/10.3390/su151914388>
- Gerwin, W., Raab, T., Birkhofer, K., Hinz, C., Letmathe, P., Leuchner, M., Roß-Nickoll, M., Rüde, T., Trachte, K., Wätzold, F., & Lehmkühl, F. (2023). Perspectives of lignite post-mining landscapes under changing environmental conditions: what can we learn from a comparison between the Rhenish and Lusatian region in Germany?. *Environmental Sciences Europe*, 35, 1-24. <https://doi.org/10.1186/s12302-023-00738-z>
- Kuter, N. (2013). Reclamation of Degraded Landscapes due to Opencast Mining. . <https://doi.org/10.5772/55796>
- Henselowsky, F., Rölkens, J., Kelterbaum, D., & Bubbenzer, O. (2021). Anthropogenic relief changes in a long-lasting lignite mining area ('Ville', Germany) derived from historic maps and digital elevation models. *Earth Surface Processes and Landforms*, 46, 1725 - 1738. <https://doi.org/10.1002/esp.5103>
- P.C. Struik, S. Amaducci, M.J. Bullard, N.C. Stutterheim, G. Venturi, H.T.H. Cromack. (2000). Agronomy of fibre hemp (*Cannabis sativa* L.) in Europe, *Industrial Crops and Products*. Volume 11, Issues 2-3, Pages 107-118, ISSN 0926-6690 [https://doi.org/10.1016/S0926-6690\(99\)00048-5](https://doi.org/10.1016/S0926-6690(99)00048-5)
- S. Amaducci, D. Scordia, F.H. Liu, Q. Zhang, H. Guo, G. Testa, S.L. Cosentino (2015). Key cultivation techniques for hemp in Europe and China. *Industrial Crops and Products*. Volume 68, Pages 2-16, ISSN 0926-6690. <https://doi.org/10.1016/j.indcrop.2014.06.041>
- S. Ahlgren, L. Björnsson, T. Prade, M. Lantz (2017). Biofuels from agricultural biomass—Land use change in Swedish perspective. f3 report.
- P. Linger, J. Müssig, H. Fischer, J. Kobert. (2002). Industrial hemp (*Cannabis sativa* L.) growing on heavy metal contaminated soil: fibre quality and phytoremediation potential. *Industrial Crops and Products*. Volume 16, Issue 1, Pages 33-42, ISSN 0926-6690. [https://doi.org/10.1016/S0926-6690\(02\)00005-5](https://doi.org/10.1016/S0926-6690(02)00005-5)
- Bhattacharyya A, Pablo CHD, Mavrodi OV, Weller DM, Thomashow LS, Mavrodi DV. (2021). Rhizosphere plant-microbe interactions under water stress. *Adv Appl Microbiol*. 115:65-113. <https://doi.org/10.1016/bs.aambs.2021.03.001>
- Hossain, M. D., Musa, M. H., Talib, J., & Jol, H. (2010). Effects of nitrogen, phosphorus and potassium levels on kenaf (*Hibiscus cannabinus* L.) growth and photosynthesis under nutrient solution. *Journal of Agricultural Science*, 2(2), 49–57. <https://doi.org/10.5539/jas.v2n2p49>
- Chimento, C., Almagro, M., & Amaducci, S. (2016). Carbon sequestration potential in perennial bioenergy crops: The importance of organic matter inputs and its physical protection. *GCB Bioenergy*, 8(1), 111–121. <https://doi.org/10.1111/gcbb.12232>
- Blanco-Canqui, H. (2016). Growing dedicated energy crops on marginal lands and ecosystem services. *Soil Science Society of America Journal*, 80(4), 845–858. <https://doi.org/10.2136/sssaj2016.03.0080>
- Boros-Lajszner, E., Wyszowska, J., & Kucharski, J. (2025). Phytoremediation properties of maize grown on heavy metal-contaminated soil and stimulated with biochar. *Environmental Science and Pollution Research International*, 32, 23361 - 23377. <https://doi.org/10.1007/s11356-025-37034-7>
- Dastyar, W., Raheem, A., He, J., & Zhao, M. (2019). Biofuel Production Using Thermochemical Conversion of Heavy Metal-Contaminated Biomass (HMCB) Harvested from Phytoextraction Process. *Chemical Engineering Journal*. <https://doi.org/10.1016/j.cej.2018.08.111>
- Hegedus, C., Paşcalău, S., Andronie, L., Rotaru, A., Cucu, A., & Dezmirean, D. (2023). The Journey of 1000 Leagues towards the Decontamination of the Soil from Heavy Metals and the Impact on the Soil–Plant–Animal–Human Chain Begins with the First Step: Phytostabilization/Phytoextraction. *Agriculture*. <https://doi.org/10.3390/agriculture13030735>
- Fernando, A., Barbosa, B., Boléo, S., Duarte, M., Sidella, S., Costa, J., & Cosentino, S. (2018). Phytoremediation Potential of Heavy Metal Contaminated Soils by the Perennial Energy Crops *Miscanthus* Spp. and *Arundo Donax* L. under Low Irrigation. , 2018, 136-139. <https://doi.org/10.5071/26theubce2018-1co.9.2>

- Rosas-Ramírez, M., Tovar-Sánchez, E., Rodríguez-Solís, A., Flores-Trujillo, K., Castrejón-Godínez, M., & Mussali-Galante, P. (2024). Assisted Phytoremediation between Biochar and *Crotalaria pumila* to Phytostabilize Heavy Metals in Mine Tailings. *Plants*, 13. <https://doi.org/10.3390/plants13172516>
- Priya, A., Muruganandam, M., Ali, S., & Kornaros, M. (2023). Clean-Up of Heavy Metals from Contaminated Soil by Phytoremediation: A Multidisciplinary and Eco-Friendly Approach. *Toxics*, 11. <https://doi.org/10.3390/toxics11050422>
- Bandyopadhyay, S., & Maiti, S. (2022). Steering restoration of coal mining degraded ecosystem to achieve sustainable development goal-13 (climate action): United Nations decade of ecosystem restoration (2021–2030). *Environmental Science and Pollution Research International*, 29, 88383 - 88409. <https://doi.org/10.1007/s11356-022-23699-x>
- Simpson, G., Ferguson, K., Slingerland, N., Jewitt, G., Alekseenko, A., Simpson, Z., Ennis-John, J., Hattingh, R., & Stock, K. (2025). Integrating the sustainable development goals into post-mining land use selection. *Scientific Reports*, 15. <https://doi.org/10.1038/s41598-025-15980-z>
- Némethy, S., & Szemethy, L. (2019). The sustainability of woody biomass feedstock production and landscape management: land use, phytoremediation, biodiversity, and wildlife habitats. *Ecocycles*. <https://doi.org/10.19040/ecocycles.v5i1.141>
- Pambudi, P., Utomo, S., Soelarno, S., & Takarina, N. (2023). Coal mining reclamation as an environmental recovery effort: a review. *Journal of Degraded and Mining Lands Management*. <https://doi.org/10.15243/jdmlm.2023.104.4811>
- Williams, M., Farr, C., Page-Dumroese, D., Connolly, S., & Padley, E. (2020). Soil Management and Restoration. *Forest and Rangeland Soils of the United States Under Changing Conditions*. https://doi.org/10.1007/978-3-030-45216-2_8
- Pratiwi., Narendra, B., Siregar, C., , I., Mulyanto, B., , S., Suryaningtyas, D., Dharmawan, I., Suharti, S., & Marsandi, F. (2025). Tin Mining and Post-Tin Mining Reclamation Initiatives in Indonesia: With Special Reference to Bangka Belitung Areas. *Land*. <https://doi.org/10.3390/land14101947>
- Simpson, G., Ferguson, K., Slingerland, N., Jewitt, G., Alekseenko, A., Simpson, Z., Ennis-John, J., Hattingh, R., & Stock, K. (2025). Integrating the sustainable development goals into post-mining land use selection. *Scientific Reports*, 15. <https://doi.org/10.1038/s41598-025-15980-z>
- Macdonald, S., Landhäuser, S., Skousen, J., Franklin, J., Frouz, J., Hall, S., Jacobs, D., & Quideau, S. (2015). Forest restoration following surface mining disturbance: challenges and solutions. *New Forests*, 46, 703 - 732. <https://doi.org/10.1007/s11056-015-9506-4>
- Mensah, A. (2015). Role of revegetation in restoring fertility of degraded mined soils in Ghana: A review. *International Journal of Biodiversity and Conservation*, 7, 57-80. <https://doi.org/10.5897/ijbc2014.0775>
- Lechner, A., Baumgartl, T., Matthew, P., & Glenn, V. (2016). The Impact of Underground Longwall Mining on Prime Agricultural Land: A Review and Research Agenda. *Land Degradation & Development*, 27, 1650 - 1663. <https://doi.org/10.1002/ldr.2303>
- Aili, A., Zhang, Y., Lin, T., Xu, H., Waheed, A., Zhao, W., Kuerban, A., Liu, K., & Dou, H. (2024). Optimizing Vegetation Restoration: A Comprehensive Index System for Reclaiming Abandoned Mining Areas in Arid Regions of China. *Biology*, 14. <https://doi.org/10.3390/biology14010023>
- Muhammad, D. (2019). Biomaterial Biochar for Soil Carbon Sequestration Strategy and Its Future Prospects. *IOP Conference Series: Earth and Environmental Science*, 391. <https://doi.org/10.1088/1755-1315/391/1/012014>
- Kowalska, A., Singh, B., & Grobelak, A. (2022). Carbon Footprint for Post-Mining Soils: The Dynamic of Net CO₂ Fluxes and SOC Sequestration at Different Soil Remediation Stages under Reforestation. *Energies*. <https://doi.org/10.3390/en15249452>
- Han, Y., , Y., Wu, C., Xiao, B., Hu, J., Shu, N., Cheng, M., & Jia, J. (2025). CO₂ Sequestration Potential and Soil Improvement Effects by Carbon-Fixing Bacteria Isolated From Degraded Soils in Shendong Coal Mining Area Located in Northwest China. *Biotechnology Journal*, 20. <https://doi.org/10.1002/biot.70108>
- Xanthopoulos, G., Radoglou, K., Derrien, D., Spyroglou, G., Angeli, N., Tsioni, G., & Fotelli, M. (2023). Carbon sequestration and soil nitrogen enrichment in *Robinia pseudoacacia* L. post-mining restoration plantations. *Frontiers in Forests and Global Change*. <https://doi.org/10.3389/ffgc.2023.1190026>
- Morris, J. (2025). A Spatial Analysis of Carbon Sequestration on Reclaimed Mine Lands. . <https://doi.org/10.33915/etd.12733>

- Ruiz, F. (2023). Carbon sequestration and mechanisms of soil organic matter stabilization in Technosols constructed for mine reclamation. . <https://doi.org/10.11606/t.11.2023.tde-13032024-150419>
- Tian, G., Granato, T., Cox, A., Pietz, R., Carlson, C., & Abedin, Z. (2009). Soil carbon sequestration resulting from long-term application of biosolids for land reclamation.. *Journal of environmental quality*, 38 1, 61-74 . <https://doi.org/10.2134/jeq2007.0471>
- Kowalska, A., Růžicková, J., Kucbel, M., & Grobelak, A. (2023). Carbon Sequestration in Remediated Post-Mining Soils: A New Indicator for the Vertical Soil Organic Carbon Variability Evaluation in Remediated Post-Mining Soils. *Energies*. <https://doi.org/10.3390/en16165876>
- Rheay, H. T., Omondi, E. C., & Brewer, C. E. (2021). Potential of hemp (*Cannabis sativa* L.) for paired phytoremediation and bioenergy production. *GCB Bioenergy*, 13(4), 525–540. <https://doi.org/10.1111/gcbb.12782>
- Ferrarini, A., Martani, E., Mondini, C., Fornasier, F., & Amaducci, S. (2022). Short-Term Mineralization of Belowground Biomass of Perennial Biomass Crops after Reversion to Arable Land. *Agronomy*, 12(2), 485. <https://doi.org/10.3390/agronomy12020485>
- Martani, E., Ferrarini, A., Serra, P., Pilla, M., Marcone, A., & Amaducci, S. (2021). Belowground biomass C outweighs soil organic C of perennial energy crops: Insights from a long-term multispecies trial. *GCB Bioenergy*, 13(3), 459–472. <https://doi.org/10.1111/gcbb.12785>
- Abreu, M., Silva, L., Ribeiro, B., Ferreira, A., Alves, L., Paixão, S. M., Gouveia, L., Moura, P., Carvalheiro, F., Duarte, L. C., Fernando, A. L., Reis, A., & Gírio, F. (2022). Low Indirect Land Use Change (ILUC) Energy Crops to Bioenergy and Biofuels—A Review. *Energies*, 15(12), 4348. <https://doi.org/10.3390/en15124348>
- Rostocki, A., Wiczorek, D., Pipiak, P., & Ławińska, K. (2024). Use of Biostimulants in Energy Crops as a New Approach for the Improvement of Performance Sequestration CO₂. *Energies*, 17(12), 2881. <https://doi.org/10.3390/en17122881>
- Peroni, P., Liu, Q., Lizarazu, W. Z., Xue, S., Yi, Z., Von Cossel, M., Mastroberardino, R., Papazoglou, E. G., Monti, A., & Iqbal, Y. (2024). Biostimulant and Arbuscular Mycorrhizae Application on Four Major Biomass Crops as the Base of Phytomanagement Strategies in Metal-Contaminated Soils. *Plants*, 13(13), 1866. <https://doi.org/10.3390/plants13131866>
- Don, A., Osborne, B., Hastings, A., Skiba, U., Carter, M. S., Drewer, J., Flessa, H., Freibauer, A., Hyvönen, N., Jones, M. B., Lanigan, G. J., Regina, K., & Sommer, M. (2012). Land-use change to bioenergy production in Europe: Implications for the greenhouse gas balance and soil carbon. *GCB Bioenergy*, 4(4), 372–391. <https://doi.org/10.1111/j.1757-1707.2011.01116.x>
- Pagnani, G., Galieni, A., D'Egidio, S., Visioli, G., Stagnari, F., Bennicelli, R. P., & Pisante, M. (2018). Effect of plant growth-promoting rhizobacteria (PGPR) on industrial hemp (*Cannabis sativa* L.) development. *Industrial Crops and Products*, 124, 514–525. <https://doi.org/10.1016/j.indcrop.2018.08.033>
- Muzammal, S., Akram, A., Shakoor, M. B., Ahmad, S. R., Khalid, M., & Hassan, S. (2023). Biochar-assisted phytoremediation for heavy metals-contaminated soils. In J. Singh, C. P. Upadhyaya, A. Kumar, & P. S. Chauhan (Eds.), *New Frontiers in Plant-Environment Interactions* (pp. 359–384). Springer, Cham. https://doi.org/10.1007/978-3-031-43729-8_13
- Randelović, D., Jakovljević, K., Zeremski, T., Poščić, F., Baltrėnaitė-Gedienė, E., Noulas, C., Mašková, P., Jurković, J., Baragaño Coto, D., Miličević, T., Cornu, J.-Y., Habyarimana, E., Sukiaysan, A., Bert, V., Renella, G., Carletti, P., Saletović, M., Maletić, S. (2025): Phytoremediation potential of metallophytes in Europe: Progress, enhancement strategies, and biomass utilization, *Journal of Environmental Management*, 391: 126516, <https://doi.org/10.1016/j.jenvman.2025.126516>
- Perlein, A., Bert, V., de Souza, M.F. Papin A, Meers E. Field evaluation of industrial non-food crops for phytomanaging a metal-contaminated dredged sediment. *Environ Science and Pollution Research* 2023. <https://doi.org/10.1007/s11356-022-24964-9>
- PERLEIN A, BERT V, FERNANDES DE SOUZA M, GAUCHER R, PAPIN A, GEUENS J, WENS A, MEERS E. 2021A. Phytomanagement of a trace element contaminated site to produce a natural dye: first screening of an emerging biomass valorization chain. *Applied Sciences*, 112, 613. <https://doi.org/10.3390/app112210613>
- PERLEIN A, ZDANEVITCH I, GAUCHER R, ROBINSON B, ARNAUD PAPIN, LOUNES-HADJ SAHRAOUI A, BERT V. 2021b. Phytomanagement of a metal(loid)-contaminated agricultural site using aromatic and medicinal plants to produce essential oils: analysis of the metal(loid) fate in the value chain. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-021-15045-4>.

PERLEIN A, **BERT V**, DESANNAUX O, FERNANDES DE SOUZA M, PAPIN A, GAUCHER R, ZDANEVITCH I, MEERS E. 2021c. The Use of Sorghum in a Phytoattenuation Strategy: A Field Experiment on a TE-Contaminated Site. **Applied Sciences**, 11, 3471. <https://doi.org/10.3390/app11083471>.

ZIEGLER-DEVIN I, MENANA Z, CHRUSCIEL L, CHALOT M, **BERT V**, BROSSE N. 2019. Steam explosion pretreatment of willow grown on phytomanaged soils for bioethanol production. **Industrial Crops and Products** 140: 111722.

ASAD M, MENANA Z, ZIEGLER-DEVIN I, **BERT V**, CHALOT M, HERZIG R, MENCH M, BROSSE N. 2017. Pretreatment of trace-element-enriched biomasses grown on phytomanaged soils for ethanol production. **Industrial Crops and Products**, 107: 63-72.

BERT V, ALLEMON J, SAJET PH, DIEU S, PAPIN A, COLLET S, GAUCHER R, CHALOT M, MICHIELS B, RAVENTOS C. 2017. Torrefaction and pyrolysis of metal-enriched poplars from phytotechnologies : effect of temperature and biomass chlorine content on metal distribution in end-products and valorization options. **Biomass and Bioenergy**, 96: 1-11.

Falconi M. et al. (2025), Phytoremediation Monograph. IMPEL, COMMON FORUM, EIONET, NICOLE report no 2022/11 PHYTO, 199 pages. Brussels, ISBN 978-2-931225-36-3.

CIADAMIDARO L, GIRARD CLOS O, **BERT V**, ZAPPELINI C, YUNG L, FOULON J, PAPIN A, ROY S, BLAUDEZ D, CHALOT M. 2017. Poplar biomass production at phytomanagement sites is significantly enhanced by mycorrhizal inoculation. **Environmental and Experimental Botany**, 139: 48-56.

GRIGNET A, DE VAUFLEURY A, PAPIN A, **BERT V (2020)**. Urban soil phytomanagement for Zn and Cd in situ removal, greening and Zn-rich biomass production taking care of snail exposure. **Environmental Science and Pollution Research**. 27: 3187-3201.

PHANTHAVONGSA P, CHALOT M, PAPIN A, LACERCAT-DIDIER L, ROY S; BLAUDEZ D, **BERT V**. 2017. Effect of mycorrhizal inoculation on metal accumulation by poplar leaves at phytomanaged sites. **Environmental and Experimental Botany**, 143 : 72-81.

Grignet A. 2021. Etude des performances de phytoextraction du Zn et du Cd de l'hyperaccumulateur *Arabidopsis halleri* en co-culture avec le saule. Thesis. P208. Ineris.

PART 2

Notice of Intellectual Property Protection: The technical specifications and production technologies for the compost described in Chapters 4-6 have been intentionally omitted to protect the commercial viability and novelty of the REECOL Project. A patent application regarding these processes is currently in preparation. Readers seeking further technical information may contact the principal investigator from the “Poltegor-Institute”.

4. Applicability tests of compost in Konin site, and influence on soil properties.

This chapter presents the results of applicability testing of the compost (developed in *Task 4.3*) at the Konin site (Józwin IIB post-mining area). The objective was to evaluate the suitability of compost application as a soil improvement measure and to assess its influence on selected soil properties under controlled field conditions.

4.1. Experimental setup

The experiment was designed to evaluate the short-term effects of compost application on soil properties and plant development under controlled, real post-mining conditions. The setup builds directly on the site characterization and degradation assessment performed in *Task 3.4* and the composting technology developed in *Task 4.3*, while remaining fully compatible with the monitoring framework established in *WP5*.

The experimental plots were established on the internal dumping ground of the Józwin IIB lignite mine, as also described in deliverable *D5.2* of the REECOL Project (Fig. 6). The area designated for agricultural reclamation. The site is characterized by anthropogenic soils formed from overburden material, exhibiting low organic matter content, limited biological activity, and altered physical structure typical of post-lignite mining landscapes. The location of the plots was selected to represent uniform geomorphological and soil conditions, minimizing the influence of slope variability and surface hydrology on experimental results.

A plot-based experimental design was applied. The experimental area was divided into three adjacent plots (Fig. 7), each further subdivided into three sub-modalities to allow composite soil sampling and reduce small-scale spatial heterogeneity.



Fig. 6 Internal dumping ground of Józwin IIB opencast. Location of experimental plots.

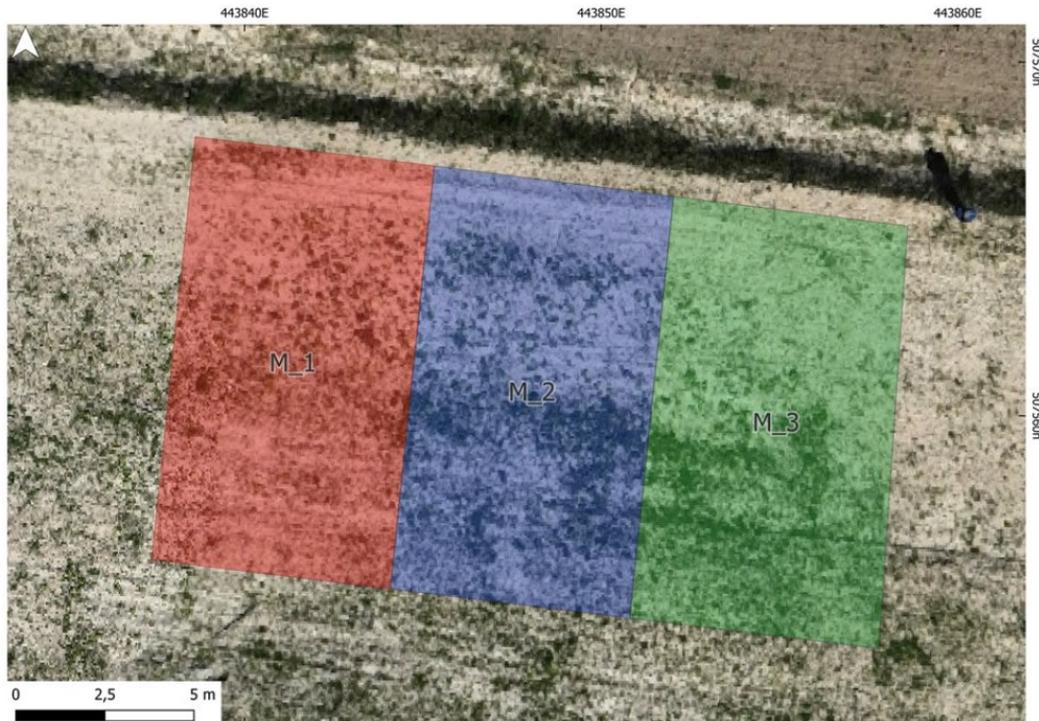


Fig. 7 Experimental setup divided into three plots. M1 and M3 plots were used for this test.

Regarding compost tests, two experimental variants were implemented:

- **Control variant (M1)** - soil without compost application, representing baseline post-mining conditions,
- **Compost-treated variant (M3)** - soil amended with compost developed within *Task 4.3* of REECOL.

The control and compost-treated plots were managed under identical conditions, ensuring that observed differences could be attributed primarily to compost application (Fig. 8).



Fig. 8 Compost application process.

Both plots were cultivated and mechanically treated on November 2024. The first series of samples was collected before compost application. Then, compost was applied in November 2024. The second series of samples was collected in April 2025.

Laboratory tests of samples were performed by project partners: *Valorhiz* and *BRGM*, as well as, laboratory of the *Faculty of Earth Sciences and Environmental Management, University of Wrocław*.

4.2. Influence of compost on soil properties

Before the application of compost, the soils in the Józwin IIB post-mining area were characterized by very low biological activity and limited fertility. Low organic matter content (OM < 0.7%, SOC ~0.4-0.5%), very low dehydrogenase activity (~0.02 DU), and poor soil microflora, which clearly indicated severe biological degradation and limited regenerative potential. The availability of key nutrients, in particular ammonium nitrogen, was very low, which was a significant limitation for plant growth.

The use of compost with high biological activity led to a marked improvement in soil functioning. An increase in enzymatic activity (dehydrogenase, phosphatase, urease), an increase in SOC, and a significant enrichment of the soil with available forms of nutrients were observed. The strongest effect was observed for ammonium nitrogen, whose content before composting increased from 19.69 mg/kg in the control soil to 43.95 mg/kg in the compost variant. At the same time, a sustained increase in the available forms of sulfur, phosphorus, potassium, and magnesium was recorded during the growing season. These changes translated into significantly better plant growth - the height of maize shoots was on average 15% greater compared to the control (as shown in *deliverable D4.3*, as part of plant growth tests). The results confirm that compost acted not only as a source of organic matter, but above all as an active factor stimulating biological processes and the circulation of nutrients in degraded post-mining soil. Chosen results are presented in tables below (Tab.1 - Tab. 3).

Tab. 1 Plant-available nutrient forms - comparison of control and compost-treated soil. **Units: mg·kg⁻¹ d.m.**

Nutrient	Nov 2024	M1 Apr 2025	M3 Apr 2025	Observation
SO ₄ ²⁻	353.45	153.23	202.69	Compost increased sulfate availability before sowing, counteracting seasonal depletion
PO ₄ ³⁻	9.57	15.25	13.59	Compost stabilized phosphate availability under alkaline soil conditions
NO ₃ ⁻	33.47	27.62	18.43	Lower nitrate levels in compost soil indicate reduced leaching and delayed mineralization
NH ₄ ⁺	19.69	1.48	43.95	Compost strongly enhanced ammonium nitrogen availability prior to sowing
K ₂ O	79.18	77.52	75.55	Potassium availability remained stable after compost application
MgO	38.31	28.20	27.19	Compost maintained magnesium availability despite seasonal decline
P ₂ O ₅	14.25	22.72	20.24	Compost supported sustained phosphorus availability before sowing

Tab. 2 Soil condition before and after compost application - selected parameters M1 and M3 plots.

Parameter	Unit	M1 Nov 2024 (I)	M1 Apr 2025 (II)	M3 Nov 2024 (I)	M3 Apr 2025 (II)
pH (H ₂ O)	–	8.70	8.87	8.67	8.87
Soil organic carbon (SOC)	g·kg ⁻¹ d.m.	4.87	6.09	3.54	7.52
Total nitrogen (Ntot)	mg·kg ⁻¹ d.m.	458	627	341	856
C/N ratio	–	10.61	9.55	10.30	8.57

Tab. 3 Enzymatic and biological indicators of soil samples (M1 vs M3). Mean values per sampling campaign. Compost applied on M3, between campaigns, in November 2024.

Microbiological Indicator	M1 2024	M1 2025	M3 2024	M3 2025	General trend
PAC	5.92	9.11	7.01	18.39	Increase over time, markedly stronger on M3
PAK	9.25	6.37	11.78	12.54	Slight decrease on M1, stable-increasing on M3
PHOS	11.24	11.00	9.40	11.77	Stable on M1, moderate increase on M3
BGLU	1.07	1.65	1.29	6.14	Strong increase on M3, minor change on M1
ARS	0.07	0.18	0.01	2.86	Marginal change on M1, sharp increase on M3
NAG	2.30	0.05	1.14	0.00	Declining trend on both plots
ARN	0.73	1.31	0.86	1.32	Moderate increase on both plots
AGLU	0.11	0.00	0.24	0.00	Decrease to near-zero values
BGAL	0.05	0.27	0.10	1.07	Increase, clearly stronger on M3
URE	5.88	4.23	5.89	4.26	Slight decrease on both plots
μRESP BR	0.58	0.58	0.78	0.85	Stable on M1, slight increase on M3
μRESP SIR	0.75	0.99	0.79	1.88	Increase on both plots, much stronger on M3

Between 2024 and 2025, the control plot (M1) shows mostly stable or moderately changing values, indicating limited natural progression of soil biological functioning. In contrast, the compost-amended plot (M3) exhibits a clear intensification of multiple indicators, particularly those related to overall biological activity and substrate processing capacity.

The strongest temporal increases are observed on M3, while M1 generally follows weaker or neutral trends. This pattern suggests that the applied amendment acted as a key driver of functional enhancement, accelerating biological processes beyond the level of spontaneous soil development. Overall, the results point to a divergent trajectory between M1 and M3, with M3 evolving toward a more biologically active and responsive system.

Note: this test was linked to short-term monitoring activities under WP5 of REECOL Project, as well as, tests of compost influence on plant growth in performed Task 4.3. The overview of all of the results will be presented in deliverable D5.3.

5. Applicability tests of compost in Velenje site, and influence on soil properties.

This chapter presents the results of applicability testing of a prepared compost at the Velenje site within post-mining area. The objective of the test was to evaluate the suitability of compost application as a soil improvement measure and to assess its influence on selected soil properties under controlled field conditions. A comparative experimental design was applied, allowing direct assessment of compost-amended soil against a mechanically treated control, based on multi-season laboratory monitoring.

5.1. Experimental setup

Applicability testing of compost was carried out at the Velenje site within a subsidence-affected mining area, characterized by disturbed soil structure and very low organic matter content. To ensure reliable comparison and minimize spatial variability, two adjacent experimental test fields were established. Each test field measured approximately 10×10 m (100 m²) and were located next to each other, under identical geomorphological and environmental conditions.

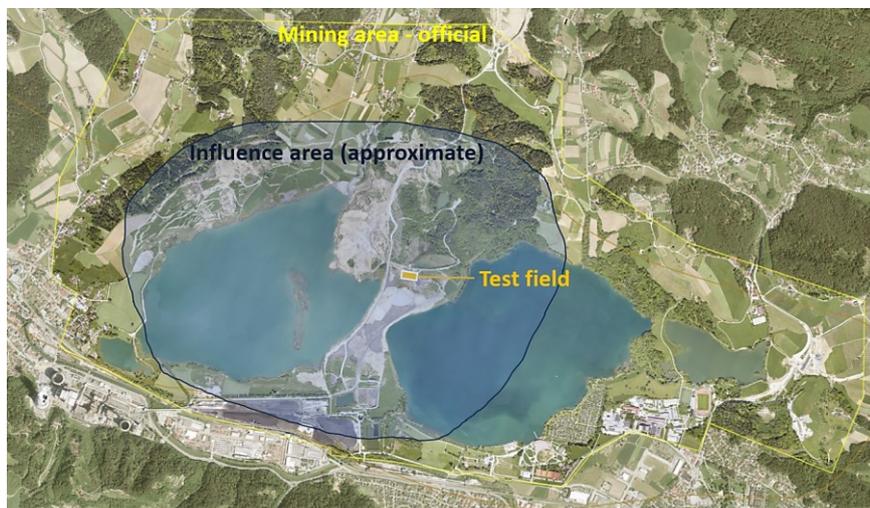


Fig. 9 Orthophoto map showing the mining area, influence zone, and the location of the experimental test field.

The experimental design consisted of Test Field A - Compost-Amended Field, where the prepared compost was applied and mechanically incorporated into the soil; and Test Field B - Control Field, where soil was subjected to mechanical treatment only, without compost addition.



Fig. 10 Orthophoto map showing Test Field A and Test Field B.

Both test fields underwent identical mechanical soil preparation, consisting of rotary tillage using a tractor-mounted tiller to the same working depth. This ensured that the presence or absence of compost was the only experimental variable.



Fig. 11 Test field after compost incorporation.

The compost used in the experiment was prepared by the “POLTEGOR-INSTITUTE” *Opencast Mining Institute, Poland*. Approximately 100 kg of compost was applied to the compost-amended test field, corresponding to an application rate of approximately 1.0 kg/m².

The compost was manually spread evenly across the soil surface and subsequently incorporated into the topsoil using a tractor-mounted rotary tiller. Compost application was performed on 18 December 2024, under dry soil and weather conditions. No further organic or mineral amendments were applied after this date. Soil monitoring was conducted during three campaigns in 2025 over one growing season in spring, summer, and winter, with samples collected from the 0-20 cm soil layer for laboratory analysis.

5.2. Influence of compost on soil properties.

The influence of compost application on soil properties was evaluated based on comparative analysis of the compost-amended and control test fields across three monitoring campaigns and two independent laboratories (*Eurofins raziskave okolja Slovenija d.o.o.* and *GIG National Research Institute, Poland*). The evaluation focused on basic sample characteristics, organic carbon fractions, soil reaction (pH), and trace metals, which together provide a comprehensive basis for assessing soil quality and environmental safety.

5.2.1. Overview of Sample Characteristics

The basic physical characteristics of the samples are comparable between treatments. This confirms that differences observed in chemical parameters can be attributed to compost application rather than sampling, handling, or preparation effects.

Tab. 4 Overview of basic sample information

Parameter	Control Field (Mechanical Treatment Only)	Compost-Amended Field	Interpretation
Soil origin	PV-REECOL parent material	PV-REECOL parent material + compost	Identical soil material
Treatment	Rotary tillage only	Compost application + rotary tillage	Compost is the only variable
Sampling depth	0–20 cm	0–20 cm	Comparable sampling layer
Dry matter	~98–99 %	~98–99 %	No compost effect
Moisture content	~1–1.6 %	~1–1.6 %	Comparable conditions

5.2.2. Organic Carbon and Soil Quality

The most consistent and relevant effect of compost application was observed in soil organic carbon content. The compost-amended field showed systematically higher total organic carbon (TOC) values compared to the control field in all monitoring campaigns. In the first (spring) campaign, the difference between the fields was small, indicating limited short-term stabilization of compost-derived organic matter. In the summer campaign (29 August 2025), both laboratories confirmed a measurable increase in TC and TOC in the compost-amended field. In the winter campaign (3 December 2025), absolute carbon contents decreased in both fields due to seasonal mineralization; however, the relative enrichment of organic carbon in the compost-amended field persisted.

Tab. 5 Carbon fractions and organic matter content (%).

Parameter	Control Field	Compost-Amended Field	Effect of compost
Total carbon (TC)	0.31–0.66	0.32–0.55	Moderate increase
Total organic carbon (TOC)	0.14–0.40	0.22–0.47	Consistent increase
Total inorganic carbon (TIC)	0.13–0.26	0.08–0.20	Neutral to slightly lower

These results demonstrate that even at a moderate application rate (~1 kg/m²), compost addition led to a detectable and persistent improvement of soil organic carbon, which is particularly significant for degraded mining soils with initially very low organic matter content.

5.2.3. Soil Reaction (pH)

Soil pH values remained within the neutral to slightly alkaline range throughout all campaigns. No consistent pH shift attributable to compost application was observed. Minor differences between the compost-amended and control fields were small, variable between extraction methods (H₂O, CaCl₂, KCl), and not environmentally significant.

Tab. 6 Soil pH Values and Interpretation

Medium	Control Field	Compost-Amended Field	Interpretation
pH (H ₂ O)	7.5–8.0	7.8–8.2	Neutral to slightly alkaline
pH (CaCl ₂)	6.9–7.7	7.3–7.7	Stable buffering
pH (KCl)	6.2–7.7	6.6–7.5	No acidification

This indicates that the applied compost had a chemically neutral effect on soil reaction and did not induce acidification or alkalization.

5.2.4. Trace Metals and Environmental Safety

Trace metal concentrations (Cu, Zn, Ni, Cr, Co, Pb) remained stable and comparable between the compost-amended and control fields throughout all campaigns. No systematic increase or decrease of any metal was observed in the compost-amended field. Cadmium (Cd) and mercury (Hg) were consistently below detection limits. Temporal variations were small and consistent with natural soil heterogeneity rather than amendment effects.

Tab. 7 Comparison of Trace Metals (mg/kg dry matter).

Metal	Control Field	Compost-Amended Field	Interpretation
Cu	~17–19	~16–18	Natural background
Zn	~68–75	~68–70	Natural variability
Ni	~23–28	~23–28	Geogenic origin
Cr	~22–33	~22–31	Mineral-controlled
Co	~11–13	~11–12	Stable background
Pb	~12–15	~12–14	No accumulation
Cd	< LOD	< LOD	No contamination
Hg	< LOD	< LOD	No contamination

These findings confirm that the compost produced by the “*Poltegor-Institute*” - *Opencast Mining Institute* did not introduce trace metal contamination and did not enhance metal mobility.

Key Findings from compost applicability test at the Velenje site:

- **Organic carbon:**
Application of prepared compost (~1 kg/m²) resulted in a consistent and measurable increase in total organic carbon (TOC) compared to the control field across all monitoring campaigns.
- **Temporal persistence:**
Although absolute carbon contents decreased seasonally, the relative enrichment of organic carbon in the compost-amended field persisted, indicating a stable amendment effect.
- **Soil reaction (pH):**
Compost application had a neutral effect on soil pH, which remained within the neutral to slightly alkaline range throughout the monitoring period.
- **Trace metals:**
Concentrations of Cu, Zn, Ni, Cr, Co, and Pb remained stable and comparable between compost-amended and control fields. Cd and Hg were consistently below detection limits.
- **Environmental safety:**
- No negative impacts, metal mobilization, or contamination risks associated with compost application were detected.

The applicability test demonstrates that compost application at the Velenje site resulted in a moderate but clearly positive effect on soil organic carbon, while having neutral effects on soil pH and trace metal concentrations. No negative impacts on soil chemical quality were detected.

From a reclamation and environmental safety perspective, the applied compost is therefore suitable for use on subsidence-affected mining soils, providing measurable improvement in soil quality without introducing chemical risks.

6. Applicability tests of compost in Mazingarbe site, and influence on soil-plant transfer of pollutants

6.1. Research hypothesis

The compost provided by Poltegor was used to maintain or reduce the soil mobility and soil-plant transfer of contaminants (metals, PAHs) while promoting the site's regeneration (ecological rehabilitation). Indeed, it was hypothesized that the compost will have a positive impact on plant growth and diversity by reducing the presence of the alien species (Caucasian hogweed), by rebalancing the carbon composition and by increasing the useful water for plant.

6.2. Experimental setup

Mid-March 2025, 6 plots on the "Hogweed" condition and 2 plots on the "oat" condition were set up (Fig. 1). The preparation consisted in the decompaction of the top-soil of each plot with a spade on 1m². Soil samples (0-20 cm depth) were collected with a hand auger before compost addition to get the initial soil properties and after soil preparation to make composites (air-dried, sieved to 2mm). On both conditions, 5 soil samples per plot were collected (i.e. 40 samples). The compost was further spread at a rate of 1.5 kg/m² following Poltegor advice on the soil of half of the "hogweed" plots (i.e. 3 plots over 6). The "oat" plots were divided in two sub-plots and compost was applied on half of each. Compost was then incorporated into the soil at a depth of 15 to 20 cm using a spade. On the "oat" modality, the incorporation was difficult due to the presence of stones. New soil samples were collected on each modality after compost incorporation (5 samples/compost plot on the "hogweed" and "oat" modalities). Composite samples were made by mixing 5 samples per plot. All composites were sent to Valorhiz and BRGM for Rockeval and biological analyses, respectively. Ineris analyzed metals, PAHs, aliphatic carbons and PFAS in the same soil composite samples.

At the beginning of May and mid-November 2025, botanical surveys were performed on all plots from both modalities (species richness, abundance-dominance ratio).

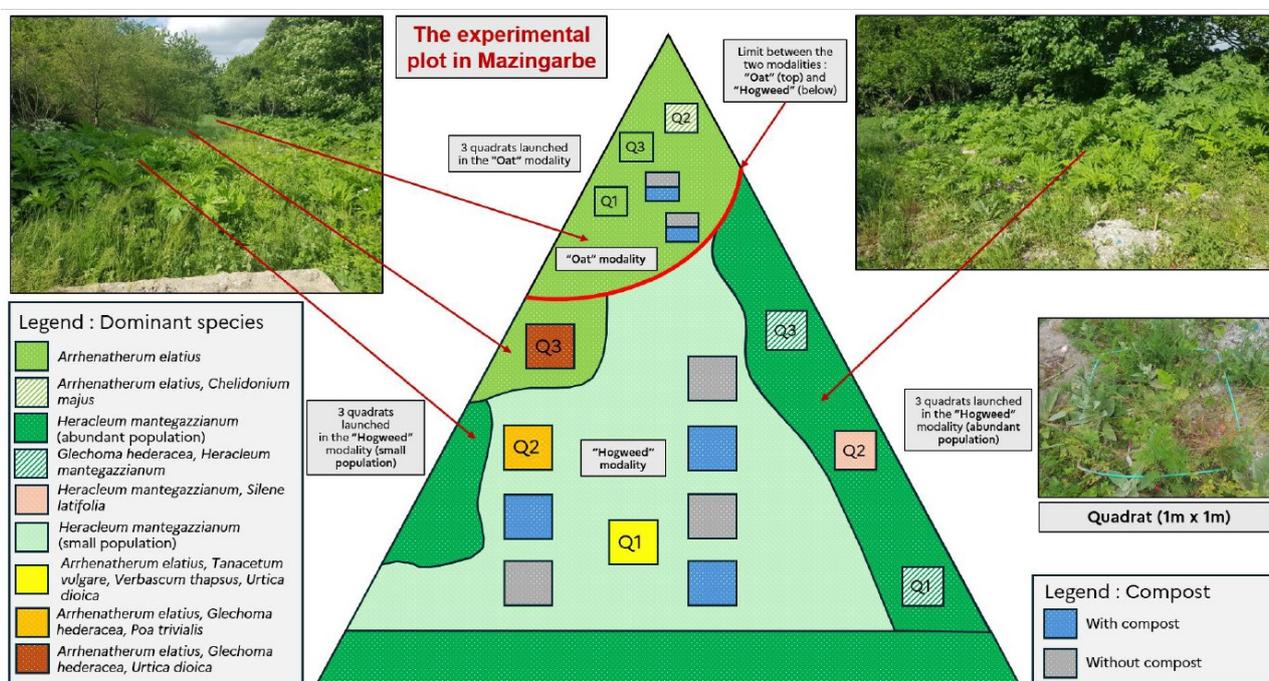


Fig. 12 Experimental design in Mazingarbe with plots dedicated to compost. Six plots were set up on the Hogweed modality of which 3 received compost. On the oat modality, 2 plots were set up which were split into 2 sub-plots, one sub-plot having received compost. Pictures show the spread of compost on plots and its mixture to the soil.

The botanical survey of mid-November 2025, around 8 months after compost incorporation, suggests that the composted soil is a favourable condition to welcome plant species. At this stage, on the hogweed modality, the species richness did not differ between both conditions, with and without compost. On the oat modality, the species richness was higher in presence of compost which can suggest that the compost is beneficial regarding this parameter. In addition, the Caucasian hogweed was not inventoried.



Fig 13 Compost application at modalities in Mazingarbe.

6.3. Influence of compost on soil transfer of pollutants and soil properties

The initial soil properties (before compost incorporation) were assessed at the beginning of the experimental field plot set up, the results belonging to *WP5* of *REECOL* (Tab. 8-9). Metal contamination in “Oat” and “Hogweed” modalities are similar except for Cr. Both modalities present high concentrations in Cd, Cr, Cu, Pb and Zn. There is no difference in metal mobility between modalities, Zn being the most mobile metal whereas Cr and Pb where the least mobile. Zn mobility approximate 1% which is quite high regarding the pH which ranges between 7.58 and 8 in oat and hogweed modalities, respectively. Other metal mobilities are low which favors horizontal and vertical limited transfer.

Other contaminant analyses evidenced PAHs and aliphatic carbons in both modalities, the oat one being more polluted than the hogweed one. PFAS were not evidenced in these soils.

Tab. 8 Total concentrations of metals in oat and hogweed soil modalities compared to the French metal soil background used in the French soil methodology on contaminated sites. In red: concentrations that exceeded the common values observed in French soils.

Total (mg/kg dry soil)	Modality		Common values observed in French soils (ASPITET database)
	Oat	Hogweed	
As	14.7 ± 0.7 a	12.7 ± 1.3 a	1.0 to 25.0
Cd	5.34 ± 0.07 a	6.01 ± 1.49 a	0.05 to 0.45
Cr	422 ± 1 a	273 ± 6 b	10 to 90
Cu	116 ± 1 a	90.7 ± 2.3 a	2 to 20
Pb	113 ± 1 a	79.5 ± 8.1 a	9 to 50
Zn	924 ± 9 a	762 ± 21 a	10 to 100

Tab. 9 Metal mobility (%) in oat and hogweed soil modalities. Mobility is calculated for each metal as the ratio between the extractable metal concentration measured with NH_4NO_3 (1M) and the total metal concentration X 100.

Percentage of mobility (%)	Modality	
	Oat	Hogweed
Zn	0.80 ± 0.07 a	0.97 ± 0.20 a
Cu	0.41 ± 0.03 a	0.60 ± 0.21 a
As	0.14 ± 0.02 ab	0.08 ± 0.01 b
Cd	0.12 ± 0.08 b	0.04 ± 0.01 b
Pb	0.02 ± 0.004 a	0.02 ± 0.01 a
Cr	0.01 ± 0,001 a	0.01 ± 0.0001 a

Analyze of extractable metals NH_4NO_3 , PAHs and aliphatic hydrocarbons were performed by *Ineris* in the soil composite samples corresponding to the ones that have received compost on both conditions (3 from the "hogweed" modality and 2 from the „oat" modality).

As expected, the incorporation of compost in the soil did not change the metal mobility in the soil, i.e. same metal mobility percentages and direction are obtained compared to the initial characterization. However, at the place of soil sampling, Zn, Cu, and Pb exhibited higher concentrations than those reported as ordinary metal soil extractable concentrations (ISO 19730 :2008(E)). Long term impact of compost addition could contribute to the reduction of this metal mobility. The new sampling planned in spring 2026, 1 year after compost incorporation, will bring answer to this hypothesis.

The addition of compost in soil could activate the biological activity in a way that organic pollutants could be degraded. Again, the new sampling planned in spring 2026, 1 year after compost incorporation, will bring answer to this hypothesis.

The same composite samples corresponding to the ones that have received compost on both conditions were analyzed by *Valorhiz* for RockEval®, pHwater, and to BRGM for the biological activities.

At this stage, the carbon speciation evidenced by RockEval® did not evidence significant change after compost incorporation compared to the initial characterization of carbon in the soil (Tab. 10). It can be expected that in the long term, the addition of compost will rebalance the carbon speciation. The new sampling planned in spring 2026 will bring answer to this hypothesis.

A decrease in pH was visible after incorporation of compost in the „hogweed" modality which in turn could increase the metal mobility. As for carbon speciation, the new sampling will tell if this pH decrease is temporary or not.

Tab. 10 Carbon speciation (Rockeval®) and organic matter results. Comparison between the initial soil status and after compost incorporation.

RockEval®	Oat modality		Hogweed modality	
	Without compost	With compost	Without compost	With compost
I(mmature) - index	0.33 ± 0.02 a	0.35 ± 0.04 a	0.09 ± 0.01 b	0.09 ± 0.12 b
R(refractory) - index	0.52 ± 0.01 b	0.50 ± 0.03 b	0.67 ± 0.01 a	0.66 ± 0.10 a
Soil Organic Carbon (g/kg)	155 ± 3 a	142 ± 2 b	60.8 ± 0.3 c	52.1 ± 0.8 d
Soil Inorganic Carbon (g/kg)	11.3 ± 0.4 c	27 ± 5 b	34.8 ± 0.2 ab	37.7 ± 4.5 a
Total OM (%)	26.7 ± 0.5 a	24.4 ± 0.4 b	10.5 ± 0.1 c	8.95 ± 0.13 d

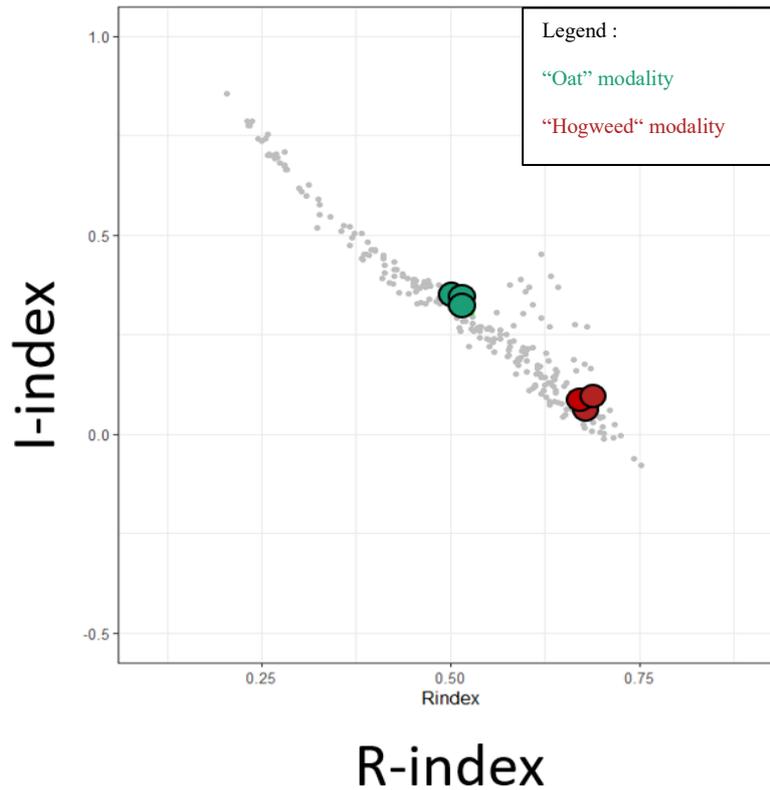


Fig. 14 The Immature-index plotted against the Refractory-index.

6.4. Short-term perspectives in Mazingarbe

A new soil sampling campaign is planned in spring 2026, 1 year after compost addition to the soil, to assess the compost gain in terms of contamination mobility and transfer (maintenance or reduction) and soil properties improvement (useful water for plants) and functionality (plant diversity, alien species reduction). Change will be interpreted by comparison of measurements before and after long-term compost application.