Call: RFCS-2024

Project no. **101216750**

COFA
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Suitability Assessment Report for Carbon Farming and Energy Crops

D3.4

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Version | 30.06.2026
Dissemination level | **Public**

Research Fund for Coal & Steel

Funded by the European Union

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Executive Summary

This report assesses the suitability of post-mining land for **carbon farming and energy crop cultivation** within the COFA project, focusing on former coal and lignite mining regions in Poland, Czechia, and Greece. Its objective is to identify the soil conditions, technical requirements, and management practices necessary to transform degraded mining landscapes into productive, climate-resilient, and economically valuable agricultural areas.

The analysis demonstrates that, despite significant environmental challenges, post-mining land can successfully support both carbon farming and renewable biomass production when reclamation is properly designed and implemented. Key limitations include soil compaction, unstable terrain, disturbed hydrology, low organic matter content, contamination risks, and altered microclimatic conditions. Successful reclamation therefore requires a combination of technical land restoration, soil improvement measures, and careful crop selection adapted to local conditions.

Carbon farming on post-mining land should not be understood as simple revegetation. Practices can only be considered carbon farming when they demonstrably increase soil organic carbon stocks, reduce greenhouse gas emissions, or support long-term carbon storage. The report highlights the importance of robust monitoring, reporting, and verification systems aligned with the EU Carbon Removals and Carbon Farming Certification Framework (Regulation EU 2024/3012). A key finding is that many existing reclamation projects create favourable conditions for carbon sequestration, but only a limited number currently provide sufficient evidence to quantify actual carbon storage benefits.

The assessment identifies several promising energy crops for reclaimed land, including **Miscanthus, willow, poplar, cardoon, common reed, and other perennial biomass species**. These crops offer multiple benefits, including soil stabilization, erosion control, phytoremediation, renewable energy production, and potential enhancement of soil organic carbon. Importantly, biomass production on reclaimed land can support climate and energy objectives without competing directly with food production on high-quality agricultural land.

Case studies from across Europe demonstrate that reclaimed mining areas can support a wide range of productive land uses, including bioenergy crops, orchards, aromatic plants, phytoremediation systems, meadow communities, and pollinator-friendly habitats. However, the report emphasizes that successful transfer of these practices requires local validation, environmental safety assessment, and long-term monitoring.

The study also highlights the broader contribution of post-mining land restoration to **climate mitigation, biodiversity enhancement, circular economy development, and Just Transition objectives**. Reclaimed landscapes can become multifunctional systems that combine renewable energy production, carbon storage, ecosystem restoration, and new economic opportunities for former mining regions.

Overall, the report concludes that carbon farming and energy crop cultivation represent realistic and valuable pathways for post-mining land reuse. The most successful approaches are those that integrate ecological restoration, productive land use, environmental safety, and long-term monitoring. While the climate benefits of many practices appear highly promising, further quantification of soil carbon accumulation is required to fully verify their contribution to climate mitigation and carbon farming objectives.

The knowledge gathered in this report will form the basis for developing scenarios for the use of post-mining land for agricultural production that promotes carbon sequestration in the soil.

1. Introduction

Coal and lignite mining have fundamentally transformed European landscapes, leading to complex forms of soil degradation that extend far beyond a simple loss of productivity.

This report constitutes the final deliverable of the COFA Project WP3 series, which focused on various aspects of agricultural reclamation of post-mining areas.

The Deliverable 3.2 titled "Soil Dysfunction Classification Report" introduces a dedicated framework for classifying "soil dysfunctions" and lays the foundation for sustainable agricultural reuse. Deliverable D3.1 titled "Regional Agricultural Reclamation Suitability Maps", establishes a methodological framework for identifying post-mining areas in Czechia, Greece, and Poland that are most suitable for agricultural reclamation. The document presents a multi-layered selection process that evaluates key "main indicators," including terrain topography (elevation and slope), land surface temperature, and water conditions, alongside "supplementary indicators" such as soil texture, vegetation vitality, and human pressure.

The Deliverable D3.3 of COFA, titled "Guidelines for Soil Regeneration and Reclamation Practices", compiles and assesses soil regeneration and agricultural reclamation practices specifically tailored to coal and lignite post-mining regions in Poland, Czechia, and Greece. The report shifts the focus from simple land stabilization to long-term soil health by aligning technical and biological interventions with specific diagnosed dysfunctions, such as compaction, acidity, or biological depletion. It identifies a range of reclamation pathways, including food, fodder, and industrial crops, while establishing high standards for food safety, soil fertility, and hydrological functionality. A central component of the document is an operational catalogue of practices, organized into ten categories, ranging from initial soil reconstruction to post-reclamation regenerative management.

This Report represents a significant advancement within the COFA project by integrating agricultural reclamation with the exploration of both carbon farming and energy crop cultivation in post-mining areas. It emphasizes sustainable land use and environmental protection, focusing on the dual objectives of restoring degraded land and promoting practices that support climate change mitigation.

Through the systematic collection and analysis of data on carbon farming practices and energy crop cultivation, this task provides a comprehensive assessment of how former of coal and lignite mining areas can be transformed into productive and environmentally sustainable agricultural landscapes.

The main objectives of this report are:

- to determine the specific soil parameters required for successful cultivation of food and energy crops;
- to identify technical challenges for land reclamation and agricultural practices that contribute to carbon sequestration and renewable energy production;
- to develop guidelines for best practices in both carbon farming and energy crop cultivation and identify ineffective practices in this area (worst practice examples).

2. Soil Requirements and Technical Challenges for Food and Energy Crops

2.1. Key Soil Parameters

A targeted review of agronomic and soil science literature identifies a core set of physical, chemical, biological, and environmental parameters that govern the establishment and productivity of energy crops on marginal and post-mining soils.

Physically, texture, bulk density, structure, aggregate stability, available water holding capacity, hydraulic conductivity, effective rooting depth, and coarse fragment content determine how water and air move, how much water is stored, how easily roots can penetrate, and how resistant the surface is to erosion.

Chemically, soil pH controls nutrient availability and toxicity risks, while soil organic carbon and organic matter underpin structure, water retention, and nutrient cycling; macronutrients (N, P, K) must be brought to sufficiency for biomass production, with secondary nutrients (Ca, Mg, S), micronutrients, cation exchange capacity, and electrical conductivity (salinity) shaping the nutrient balance and crop tolerance envelope.

Biologically, microbial biomass and enzyme activity indicate whether decomposition and nutrient cycling have recovered after disturbance, while soil fauna and root biomass reflect progressing ecosystem function and carbon inputs below ground.

Environmentally, potential contaminants (heavy metals, organic pollutants), erosion susceptibility, groundwater level, and local hydrology constrain land use choices and species placement and influence both reclamation success and carbon outcomes.

To make these findings actionable for screening and design, each parameter in the table below (Table 1**Błąd! Nie można odnaleźć źródła odwołania.**) is tagged for its direct relevance to energy crops (YES), recommended monitoring to optimize outcomes (RECOMMENDED), or conditional consideration where constraints may limit agriculture or require remediation (CONDITIONAL). The accompanying sources synthesize broad evidence across marginal/post-mining contexts, ensuring the matrix that follows is grounded in established relationships rather than site-specific assumptions.

Table 1. List of key physicochemical soil parameters in the context of energy crop cultivation

Category	Soil parameter	Importance for reclamation, carbon farming and energy crop cultivation	For Energy Crops	Source
Physical	Soil texture (sand, silt, clay)	Determines water retention, aeration, and nutrient availability.	**YES**	*Arshad et al. 2015* *Dexter 2004* *Singh et al. 2022*
	Bulk density	High bulk density indicates soil compaction, restricting root development, water infiltration, and biological activity.	**YES**	*Arshad et al. 2015* *Dexter 2004* *Worlanyo & Li 2020* *Singh et al. 2022*
	Soil structure and aggregate stability	Influences erosion resistance, water movement, and long-term carbon stabilization.	**YES**	*Arshad et al. 2015* *Rabot et al. 2018* *Dexter 2004*
	Available Water Holding Capacity (AWHC)	Determines the amount of water available for plants and drought resilience.	**YES**	*Singh et al. 2022* *Dexter 2004* *Arshad et al. 2015*
	Hydraulic conductivity / infiltration	Controls drainage, runoff, and water availability for vegetation.	**YES**	*Dexter 2004* *Arshad et al. 2015* *Morcillo et al. 2023*
	Effective rooting depth	Determines the volume of soil accessible for root growth and nutrient uptake.	**YES**	*Arshad et al. 2015* *Dexter 2004*
	Coarse fragment (stone) content	High stone content reduces effective rooting volume and water storage capacity.	**RECOMMENDED**	*Arshad et al. 2015* *Worlanyo & Li 2020*
Chemical	Soil pH	Controls nutrient availability, microbial activity, and crop suitability.	**YES**	*Chaudhry et al. 2024* *Nguemezi et al. 2020* *Kwiatkowski & Harasim 2020* *Worlanyo & Li 2020*
	Soil Organic Carbon (SOC)	Primary indicator of soil fertility and carbon sequestration potential.	**YES**	*Kwiatkowski & Harasim 2020* *Chaudhry et al. 2024* *Singh et al. 2022*

	Soil organic matter (SOM)	Improves soil structure, water retention, nutrient cycling, and biological activity.	**YES**	*Chaudhry et al. 2024 Nguemezi et al. 2020 Kwiatkowski & Harasim 2020*
	Nitrogen (N) Phosphorus (P) Potassium (K)	Essential macronutrients required for plant growth and biomass production.	**YES**	*Chaudhry et al. 2024 Nguemezi et al. 2020 Kwiatkowski & Harasim 2020*
	Calcium (Ca) Magnesium (Mg) Sulfur (S)	Important for soil structure, nutrient balance, and plant development.	**RECOMMENDED**	*Chaudhry et al. 2024 Nguemezi et al. 2020 Kwiatkowski & Harasim 2020*
	Micronutrients	Deficiencies or excesses may limit plant growth and productivity.	**RECOMMENDED**	*Kwiatkowski & Harasim 2020 Chaudhry et al. 2024*
	Cation Exchange Capacity (CEC)	Indicates the soil's capacity to retain and supply nutrients.	**RECOMMENDED**	*Nguemezi et al. 2020 Kwiatkowski & Harasim 2020 Chaudhry et al. 2024*
	Electrical Conductivity (EC)	Measures soil salinity, which can limit crop establishment and growth.	**CONDITIONAL**	*Nguemezi et al. 2020 Worlanyo & Li 2020 Kwiatkowski & Harasim 2020*
Biological	Microbial biomass and activity	Indicates biological recovery and nutrient cycling processes.	**RECOMMENDED**	*Bonilla-Bedoya et al. 2023 Daunoras et al. 2024*
	Enzyme activity	Reflects the intensity of biological processes involved in organic matter decomposition and nutrient cycling.	**RECOMMENDED**	*Daunoras et al. 2024 Bonilla-Bedoya et al. 2023*
	Soil fauna (e.g. earthworms)	Indicates biological soil quality and ecosystem functioning.	**RECOMMENDED**	*Bonilla-Bedoya et al. 2023 Singh et al. 2022*
	Root biomass	Reflects vegetation establishment and carbon inputs into the soil.	**YES**	*Singh et al. 2022 Morcillo et al. 2023 Worlanyo & Li 2020*
Environmental	Heavy metal concentrations (Pb, Cd, Zn, Ni, Cr, As, Hg)	Determine food safety and influence appropriate land-use options.	**CONDITIONAL**	*Haghighizadeh et al. 2024 Worlanyo & Li 2020*

	Organic contaminants	May restrict agricultural use and require remediation.	**CONDITIONAL**	*Sun et al. 2018*
	Erosion susceptibility	Affects long-term soil stability and the preservation of soil organic carbon.	**YES**	*Worlanyo & Li 2020* *Morcillo et al. 2023*
	Groundwater level and hydrological conditions	Influence crop selection, soil moisture, and reclamation success.	**YES**	*Morcillo et al. 2023* *Singh et al. 2022* *Worlanyo & Li 2020*

2.2. Technical Limitations

When evaluating post-mining areas for agricultural reclamation, the challenges extend far beyond the soil itself. The sheer scale of earth-moving and underground extraction fundamentally alters the landscape's structure, water systems, and even its thermal dynamics.

The morphological, hydrological, geotechnical and thermal challenges that must be resolved to make these areas suitable for agriculture.

Morphological and Topographical Challenges

In areas with a history of underground mining, the collapse of of underground mine workingscauses uneven surface settling (subsidence and sinkholes). This creates unpredictable sinkholes, localized depressions, and fractured terrain. Properly conducted technical reclamation is essential in this case to ensure that heavy agricultural equipment can operate on the site.

Spoil heaps and waste rock dumps are often constructed with steep slopes to minimize their footprint (steep slope). Gradients that exceed 10–15% severely limit or prohibit mechanized farming, increase the risk of machinery rollover, and dictate what types of crops or pasture can be safely managed.

Reclaimed land is often constructed unconsolidated spoil (excavated rock and earth). Over years or decades, this material settles unevenly. This continuous shifting makes it extremely difficult to grade the land for precision agriculture or establish permanent field boundaries.

Hydrological Disruptions

During active mining, constant pumping artificially lowers the regional water table, creating a "cone of depression." Once mining ceases and pumping stops, the groundwater rebounds unpredictably. This can turn top soil stranded above the new water table, making them hyper-susceptible to drought. Natural landscapes have aquifers, wetlands, and subterranean structures that buffer against dry seasons. Post-mining topographies often drain too quickly leading to decreasing water availability for crops. In areas of former underground mining (like hard coal), the surface subsidence, alter surface water flow, and cause area flooding (Pierzchała et all 2016). Mining operations could also completely obliterate historical surface water networks. Restoring agricultural viability requires artificially engineering new macro-drainage systems to prevent excessive runoff from scouring the landscape or flooding low-lying areas (Nicolau et all 2002).

Hydrological changes affect not only the availability of water to plants (waterlogging and drought) but also the ability to use agricultural equipment. Both dry, heavy soil and excessively wet soil limit the use of heavy agricultural equipment. In the case of heavy, dry soils, it is difficult to perform agricultural operations such as plowing. Wetlands, on the other hand, due to their lower load-bearing capacity, require the use of specialized drive systems (e.g., tracked drives) to prevent agricultural equipment from sinking into the ground.

Thermal and Geothermal Hazards

Spontaneous Combustion is a critical hazard specifically on hard coal and lignite waste heaps (endogenic fires). Residual coal dust and pyrites exposed to oxygen can spontaneously ignite deep within the heap. These slow-burning, underground fires bake the root systems of any surface vegetation, emit toxic gases, and create hidden, hollow cavities that can collapse without warning. In extreme cases of heavy soot accumulation, vegetation may die off completely, leading to the elimination of crops on the surface of the coal ash dump. Even without internal reinforcement the raw geological materials left behind—particularly dark shales and coal waste—absorb massive amounts of solar radiation. Surface temperatures on dark spoil heaps can easily exceed 50–60°C in the summer. This lethal heat bakes seedlings, destroys the microclimate needed for plant establishment, and accelerates moisture evaporation (Musiałek et al 2024).

Severe Compaction

Decades of heavy machinery operation compress the soil profile, destroying macroporosity. Highly compacted soil restricts root penetration, limits oxygen availability to plant roots, and drastically reduces water infiltration, leading to surface runoff and limits or hinders the performance of soil cultivation practices (e.g. plowing, planting) In the case of a waste rock dump whose grain size distribution is dominated by stones and gravel, it is practically impossible to carry out operations that require disturbing or digging through compacted surfaces.

Agricultural reclamation of post-mining areas requires a comprehensive approach that includes land stabilization, water management, elimination of thermal hazards, and improvement of the physical properties of the soil. Only after these issues have been resolved is it possible to use such areas for agricultural purposes in a sustainable and safe manner.

Despite a wide range of risks and limiting factors, the cultivation of energy crops and carbon farming in post-mining areas is possible. Key to overcoming technical challenges is both the proper implementation of technical reclamation and the appropriate selection of crop species and cultivation methods.

3. Carbon Farming Practices

3.1. Relevance of carbon farming for post-mining areas

Carbon farming on post-mining land can be defined as a set of land use practices that support the restoration of soil functions, reduce carbon losses from the soil ecosystem, and lead to an increase in soil organic carbon stocks or the temporary storage of carbon in biomass. In this sense, carbon farming is not equivalent to mere greening of the land, to establishing energy crop plantations, or to any form of biological reclamation. A given practice can be classified as carbon farming only if its environmental and climate effects can be referenced against the baseline soil condition and monitored over time (Bilandžija et al., 2021; Jeżowski et al., 2017; Regulation (EU) 2024/3012).

The specificity of post-mining areas stems from the fact that carbon sequestration potential is largely determined by the properties of the substrate. These lands often lack a fully developed soil profile and are characterized by low organic matter content, disturbed structure, limited water retention, unfavorable pH, reduced biological activity, or the presence of contaminants. For this reason, carbon farming practices should be analyzed in connection with the process of rebuilding the root zone and soil functions, rather than solely through the lens of the plants' capacity to produce biomass (Jeżowski et al., 2017; Malinská et al., 2020; Nelson et al., 2025).

The assessment of carbon farming practices on post-mining land requires distinguishing three interrelated components: utility, safety, and climate effect. Utility refers to a given practice's ability to stabilize the terrain, improve soil properties, establish permanent vegetation cover, or produce biomass. Safety encompasses controlling the risk associated with the presence of contaminants in soil, biomass, water, ash, digestates, and products intended for human or animal consumption. The climate effect refers to the ability to demonstrate changes in soil organic carbon (SOC) stocks, reductions in soil emissions, or to establish a reliable carbon balance covering the soil–plant system (Janas & Zawadzka, 2017; Newton et al., 2025; Stolarski et al., 2015).

The most important interpretive limitation concerns the relationship between biomass production and carbon sequestration. A high yield of energy crops does not, by itself, constitute proof of an increase in soil carbon stocks. Assessing the carbon balance requires accounting for both carbon inputs and losses, including aboveground and belowground biomass, crop residues, soil respiration, agrotechnical operations, and biomass removal with the harvest. Consequently, biomass yield should be treated as an indicator of the production and functional efficiency of a given practice, not as a direct measure of the carbon sequestration effect (Bilandžija et al., 2021; da Costa et al., 2019).

3.2. Methodological and regulatory framework for assessing carbon farming practices

Assessing the climate effects associated with carbon farming requires the use of procedures that ensure their measurability, comparability, and interpretive reliability. In practice, this means the necessity of establishing a baseline, monitoring changes in soil organic carbon content, defining the sampling depth, accounting for soil bulk density, and systematically documenting land use practices. The absence of this information makes it impossible to reliably quantify changes in soil carbon stocks or to assess their relationship with the applied intervention (Bilandžija et al., 2021; Regulation (EU) 2024/3012).

This approach is reflected in current European Union regulations. Regulation (EU) 2024/3012 defines carbon farming as a practice or process carried out for a period of at least five years, related to the management of terrestrial or coastal environments, leading to the capture and storage of atmospheric or biogenic carbon in biogenic pools, or to the reduction of greenhouse gas emissions from soil. The regulation also requires the conservative treatment of uncertainties related to the quantification of effects and the monitoring of the risk of loss of previously accumulated carbon, in order to ensure the permanence of the declared climate benefits (Regulation (EU) 2024/3012).

Also regulatory relevant are activities involving the use of organic amendments, fertilizing products, biostimulants, biochar, composts, sludges, and materials derived from recovery processes. Regulation (EU) 2019/1009 sets out the rules for placing EU fertilizing products on the market, emphasizing the need to ensure the safety of humans, animals, plants, and the environment. With regard to recovered materials, such as biochar or ash-based products, the regulation provides for separate technological, quality, and environmental criteria, as well as an obligation to control their production process (Regulation (EU) 2019/1009).

Of particular importance is Delegated Regulation (EU) 2021/2088, under which materials derived from pyrolysis and gasification processes were included in the category of component materials for EU fertilizing products. However, their placement on the market is conditional on meeting the requirements concerning safety, labeling, and conformity assessment procedures. This means that biochar and other carbon-based materials used in carbon farming practices require, in each case, an assessment of quality, feedstock origin, technological process parameters, and compliance with applicable regulatory requirements (Delegated Regulation (EU) 2021/2088).

Where practices are carried out on degraded land using crops intended for human consumption or feed, contamination control is crucial. Regulation (EU) 2023/915 sets the maximum permissible levels of selected contaminants in food and imposes an obligation to keep them as low as reasonably achievable while observing good production practice. This means that soil quality improvement or good plant condition do not constitute a sufficient basis for considering the yield to be safe. Introducing products into the food chain requires confirming their health quality on the basis of appropriate analyses (Regulation (EU) 2023/915).

In the case of biomass intended for energy purposes, the safety assessment focuses on the quality of the feedstock and the properties of the products generated in the processes of its conversion. Energy willow can accumulate heavy metals present in the soil environment, which are concentrated in ash during combustion, limiting the possibilities of its further use, including agricultural use (Janas & Zawadzka, 2017). Similar requirements apply to miscanthus biomass obtained from land with a varied use history. Its energy usefulness requires the assessment of physicochemical parameters, including calorific value, ash content and ash properties influencing the thermochemical processing of biomass (Newton et al., 2025).

The presented methodological and regulatory requirements constitute the basis for a unified description and assessment of carbon farming practices, enabling the distinction between reclamation activities, production activities and actual carbon sequestration effects.

3.3. Standard for describing carbon farming practices

Good carbon farming practices should be presented according to a unified description scheme, enabling their use value, environmental safety and climate component to be taken into account simultaneously. Such a scheme ensures the comparability of analyses and reduces the risk of overinterpreting the results. In this approach, a given solution may hold significant environmental or reclamation value even in the absence of a complete dataset on SOC (soil organic carbon) changes. However, the status of a given practice should be defined precisely - as a reclamation practice, a biomass production practice with carbon farming potential, or a practice with a confirmed sequestration component (Bilandžija et al., 2021; Makovníková et al., 2025; Reinhardt et al., 2021).

Table 2. Standard description of carbon farming practices in post-mining and degraded areas

Description element	Scope of information	Significance for practice interpretation	Literature
Site context	Land type, nature of degradation, land-use history, basic soil properties and water conditions	Determines the conditions to which the practice applies and whether its results can be interpreted in the context of post-mining areas	Jeżowski et al. (2017); Malinská et al. (2020); Reinhardt et al. (2021)
Practice objective	Remediation, stabilization, biomass production, phytostabilization, phytoremediation, SOC increase, retention improvement	Distinguishes the reclamation, production, and climate functions	Bilandžija et al. (2021); Nelson et al. (2025); Souki et al. (2021)
Applied practice	Species, variety or clone, establishment method, cultivation system, fertilization, soil amendments, supporting treatments	Allows assessment of whether the outcome results from species properties or from the entire intervention package	Jeżowski et al. (2017); Sulima et al. (2017); Smart & Cameron (2008)
Usefulness	Survival rate, vegetation cover, plantation stability, yield, biomass quality, improvement of soil functions	Defines the practical value of the solution but does not determine the carbon farming effect	Lisowski et al. (2018); Newton et al. (2025); Sater et al. (2025)
Environmental safety	Metals, salinity, organic contaminants, leaching risk, quality of biomass, ash or digestate	Limits the risk of contaminant transfer to the environment or to products	Burdová et al. (2023); Janas & Zawadzka (2017); Regulation (EU) 2023/915
Carbon farming component	SOC, SOM, baseline, sampling depth, bulk density, C balance, monitoring period	Determines whether the practice can be interpreted as carbon farming or only as reclamation or biomass production	Bilandžija et al. (2021); Regulation (EU) 2024/3012
Conditions for success	pH, texture, retention, water availability, drought, salinity, variety, plantation age, fertilization, mechanization	Indicates the factors determining the effectiveness of the practice	Kuzovkina et al. (2018); Lafleur et al. (2017); Palm et al. (2022); Teagasc (2025)

Transferability	Types of sites to which the practice can be transferred, boundary conditions, need for local validation	Prevents mechanical copying of practice between different areas	Reinhardt et al. (2021); Renninger et al. (2024); Sater et al. (2025)
Limitations	Lack of SOC data, short observation period, risk of contamination, costs, transport, no biomass recipient	It indicates what cannot be concluded from a given case	Stolarski et al. (2015); Newton et al. (2025); Regulation (EU) 2024/3012
Final interpretation	Practice status: carbon farming, reclamation practice, production practice with carbon farming potential, practice requiring validation	It gives a practice a precise qualification without overstating its importance	Bilandžija et al. (2021); Jeżowski et al. (2017); Makovníková et al. (2025)

The basic condition for interpretation is separating empirically confirmed results from effects that remain at the level of potential benefits. An example may confirm the suitability of a given species for soil stabilization or biomass production; however, in the absence of data on SOC changes, it should not be classified as a fully confirmed carbon farming practice. Similarly, the carbon balance developed for marginal lands can be an important methodological reference point, but its direct transfer to post-mining technologies requires prior verification of local soil, water and technological conditions (Bilandžija et al., 2021; Reinhardt et al., 2021).

Transferability of practice should be understood as the possibility of transferring the conditions of effectiveness, and not just the use of the same plant species. The literature on energy crops indicates that the yield and quality of biomass result from the interaction between the genotype, soil properties, climatic conditions, water availability, salinity, nutrient content and the applied technology of use. This applies both to willow, whose productivity is strongly dependent on habitat properties, genotype, and climatic conditions, and to miscanthus, whose response to environmental stress and biomass quality change with habitat conditions and plantation age (Kuzovkina et al., 2018; Lafleur et al., 2017; Malinská et al., 2020; Newton et al., 2025; Palm et al., 2022).

The description of actions analyzed within carbon farming should lead to a balanced and unambiguous interpretation of their environmental significance. Solutions that meet the usability criterion may be classified as effective reclamation or production activities. If their environmental safety is additionally demonstrated, they may be recommended for implementation in specific habitat and technological conditions. However, the status of carbon farming activities in the strict sense of the term should be granted only when data are available confirming an increase in SOC resources, a positive carbon balance or a permanent reduction in carbon losses from the soil system (Bilandžija et al., 2021; Regulation (EU) 2024/3012; Stolarski et al., 2015).

4. Energy Crop Cultivation

4.1. Suitable Species and Cultivation Parameters

The selection of appropriate energy crops is a fundamental step in transforming post-mining landscapes into productive areas that support both renewable energy and climate goals. Given that former mining sites often suffer from significant soil dysfunctions - including compaction, acidification, and altered water cycles - the success of any agricultural reclamation depends on matching specific plant traits with the unique limitations of the land.

To address these challenges, a comparative assessment table has been developed as a practical decision-support tool for the COFA project regions in Poland, the Czech Republic, and Greece. This table is provided in the **Annex 1**. Its purpose is to provide a structured overview of energy crop species, linking their agronomic potential with their ability to withstand the harsh conditions of reclaimed sites. In the broader project context, it facilitates the integration of biomass production with carbon farming, helping to identify species that effectively sequester carbon while restoring long-term soil health.

The species included in the table were selected to represent different plant groups, namely trees and shrubs, grasses, perennials, and annual allowing for a broad comparison of options depending on site conditions and intended crop use.

The table consolidates a wide array of technical and environmental parameters necessary for informed land management. It captures technical factors such as biomass yield across different climate regions, calorific value, and intended crop use. On the agronomic side, it specifies soil requirements including optimal pH, nutritional demands, and preferred substrate texture, which are critical for assessing compatibility with disturbed post-industrial soils.

Furthermore, the table evaluates the resilience of each species through a set of meteorological and resistance indicators. These include tolerance to drought, heat waves, and spring frosts, as well as resistance to soil-specific stresses like erosion, compaction, salinization, and contamination. By bringing together these diverse datasets, the table provides a comprehensive basis for selecting species that are not only productive but also capable of thriving in challenging post-industrial environments, ensuring that reclamation efforts are both ecologically effective and economically viable.

5. Land use, climate mitigation and energy production synergies

5.1. Contribution of post-mining land reclamation to climate change mitigation

Mining activities remove topsoil, disturb soil aggregates, expose carbon-poor substrates and interrupt natural carbon cycling. Consequently, post-mine soils often exhibit low organic matter content, reduced microbial activity and limited carbon storage capacity. Without ecological restoration, these degraded substrates may remain persistent sources of greenhouse gas emissions through ongoing organic matter oxidation, erosion and limited biological productivity. The recovery of these degraded ecosystems therefore represents not only an environmental restoration challenge but also an opportunity to enhance long-term carbon sequestration and support climate change mitigation.

Land systems play a dual role in the global climate system, acting both as sources and sinks of greenhouse gases (Lal, 2004). Consequently, restoration and sustainable land management have become increasingly important components of climate change mitigation. In this context, post-mining land reclamation can be considered part of the Agriculture, Forestry and Other Land Use (AFOLU) sector, which encompasses managed terrestrial ecosystems and land-based mitigation activities. According to Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report (AR6)[1] Working Group III, AFOLU measures include ecosystem protection, restoration, improved land management, soil carbon enhancement and bioenergy production (Nabuurs et al., 2022; Pathak et al., 2022). These measures are increasingly recognized as natural climate solutions and nature-based solutions capable of simultaneously reducing greenhouse gas emissions, enhancing carbon removals and delivering multiple environmental co-benefits. The growing importance of AFOLU is reflected in international climate policy, with land-based measures incorporated into the Nationally Determined Contributions (NDCs) of the majority of countries participating in the Paris Agreement (Griscom et al., 2017; Roe et al., 2021).

Post-mining land reclamation can also be understood within the broader framework of Nature-based Solutions (NBS), which use ecosystem restoration and sustainable land management to address societal challenges such as climate change, biodiversity loss and land degradation. Within this framework, reclamation extends beyond site rehabilitation by restoring ecosystem functions that support long-term carbon sequestration, biodiversity recovery and climate resilience. Consequently, post-mining restoration represents a multifunctional land management approach capable of delivering multiple environmental co-benefits alongside greenhouse gas mitigation (Griscom et al., 2017; Seddon et al., 2020; Roe et al., 2021).

The IPCC AR6, Working Group III further identifies restoration of degraded ecosystems as one of the most effective land-based climate mitigation options, owing to its potential to enhance carbon sinks while reducing emissions associated with land degradation (Nabuurs et al., 2022; Pathak et al., 2022). This conclusion is consistent with a growing body of scientific evidence demonstrating that ecosystem restoration constitutes an essential component of global climate mitigation strategies. According to Roe et al. (2021), land-based measures could provide approximately 20-30% of the mitigation required to achieve the 1.5°C target by mid-century, while simultaneously supporting biodiversity conservation, ecosystem restoration, climate adaptation and other sustainable development objectives.

During the period 2010–2019, the AFOLU sector accounted for approximately 13–21% of total anthropogenic greenhouse gas emissions, while managed and natural terrestrial ecosystems simultaneously absorbed around one-third of anthropogenic CO_2 emissions. When both managed and natural land sinks are considered, terrestrial ecosystems collectively constituted a net sink of approximately 6.6 ± 5.2 Gt CO_2 yr^{-1} during the same period (Nabuurs et al., 2022). These figures illustrate the critical role of land management in determining whether ecosystems function as net emitters or net removers of atmospheric carbon. In mitigation pathways consistent with limiting global warming to 1.5°C under the Paris Agreement, the rapid deployment of AFOLU measures is therefore considered essential (IPCC, 2018; Roe et al., 2019). The overall mitigation potential of restoration, protection and improved ecosystem management has been estimated at 3.9–13.1 Gt CO_2-eq yr^{-1} globally, with a mean value of approximately 7.3 Gt CO_2-eq yr^{-1} (Nabuurs et al., 2022; Pathak et al., 2022).

Within this context, the restoration of degraded land is recognized by the IPCC as one of the most cost-effective land-based mitigation measures. The reclamation of post-mining areas represents a particularly relevant application of these principles because mining activities create extensive areas characterized by severely disturbed carbon cycles, depleted biological productivity and low carbon storage capacity. This applies both to opencast mining sites, where topsoil removal and large-scale earth movement disrupt entire soil profiles, and to spoil heaps, waste dumps and subsidence areas associated with underground coal mining. In all of these cases, the resulting substrates typically contain low concentrations of organic carbon and exhibit limited capacity for carbon storage. Consequently, reclaimed post-mining landscapes possess substantial potential for additional carbon accumulation compared with more mature ecosystems, making them attractive targets for climate mitigation interventions. Such areas are particularly attractive from a climate policy perspective because they allow carbon removals and, where appropriate, sustainable biomass production to be increased without requiring the conversion of natural ecosystems or productive agricultural land, thereby avoiding one of the major trade-offs frequently discussed in relation to large-scale land-based mitigation measures (Roe et al., 2021). This aspect is particularly relevant in densely populated and highly transformed mining regions, where opportunities for creating additional carbon sinks are often limited by competing land-use demands.

One of the key mechanisms through which reclaimed post-mining lands contribute to climate mitigation is the sequestration of atmospheric carbon in both soil and plant biomass. According to IPCC AR6 WGIII, soil carbon management, ecosystem restoration and vegetation establishment constitute important carbon dioxide removal pathways within the AFOLU sector. Carbon sequestration occurs through the accumulation of aboveground biomass, root-derived organic matter and microbial residues, which progressively increase Soil Organic Carbon (SOC) stocks. A substantial proportion of these carbon inputs originates from belowground biomass, including fine-root turnover and rhizodeposition, which play a fundamental role in the formation and long-term stabilization of soil organic matter (Lal, 2018; Sokol et al., 2019). Healthy soils constitute one of the largest terrestrial carbon reservoirs and play a crucial role in regulating the global carbon cycle. Consequently, the restoration of degraded soils has been recognized as an essential component of climate neutrality strategies (European Commission, 2021). The IPCC identifies soil carbon enhancement among the major land-based mitigation options capable of contributing to global emission reduction efforts while simultaneously improving ecosystem resilience.

Among the various terrestrial carbon pools, Soil Organic Carbon (SOC) represents the principal long-term carbon reservoir restored during post-mining reclamation. The increase in Soil Organic Carbon (SOC) is particularly important in reclaimed mining landscapes. Soil organic carbon is widely recognized as a key indicator of soil health because it regulates nutrient cycling, aggregation processes, water retention and microbial activity (Lal, 2004; FAO, 2020). Because post-mining lands generally contain very low initial stocks of soil organic carbon and biomass, reclamation activities offer substantial opportunities for generating additional carbon removals. From a climate mitigation perspective, such areas frequently provide higher relative sequestration gains than mature ecosystems where carbon stocks have already approached equilibrium levels. In post-mining substrates, where SOC stocks are typically depleted by excavation, erosion and oxidation processes, reclamation-induced carbon accumulation contributes not only to climate mitigation but also to the recovery of essential soil functions. The restoration of SOC creates positive feedback mechanisms whereby improving soil quality enhances vegetation productivity, which in turn generates additional carbon inputs and further increases carbon storage capacity.

The long-term climate benefits of post-mining land reclamation depend not only on the rate of carbon accumulation but also on the permanence of carbon storage. Maintaining stable vegetation cover, minimizing soil disturbance and applying sustainable land management practices are therefore essential for ensuring that accumulated carbon remains stored in biomass and soils over extended periods. Consistent with IPCC recommendations, robust monitoring, reporting and verification (MRV) systems are required to quantify changes in soil organic carbon and biomass stocks. Reliable carbon accounting is particularly important if reclaimed post-mining sites are to be integrated into emerging carbon farming and carbon certification schemes. The importance of long-term monitoring has also been highlighted in life-cycle assessments of reclaimed mine lands, demonstrating that the net climate benefits of reclamation depend on both the magnitude and the permanence of carbon sequestration (Littlefield et al., 2013). Furthermore, MRV systems constitute a fundamental prerequisite for participation in the Carbon Removals and Carbon Farming Certification Framework (CRCF) established under Regulation (EU) 2024/3012.

The magnitude and mechanisms of carbon sequestration differ among post-mining land types. In reclaimed opencast mines, carbon accumulation is primarily associated with large-scale soil reconstruction, afforestation and the establishment of permanent grassland communities. Over time, newly developing soils may gradually rebuild significant SOC stocks while growing vegetation accumulates carbon in woody biomass and root systems. In contrast, spoil heaps and waste dumps commonly found in former underground coal mining regions, such as those widespread in Upper Silesia, often require engineered reclamation measures to overcome unfavourable physical and chemical properties. The application of organic amendments, composts, sewage sludge, digestates or other waste-derived materials may accelerate soil-forming processes, increase microbial activity and promote vegetation establishment, thereby initiating long-term carbon sequestration pathways.

Depending on site-specific conditions, reclamation may involve afforestation, establishment of semi-natural grasslands, biomass production systems or mixed multifunctional land-use configurations. These reclamation pathways differ in the relative contribution of biomass and soil carbon accumulation. Afforestation generally maximizes long-term carbon storage in aboveground biomass, whereas perennial grasslands and biomass production systems frequently allocate a greater proportion of assimilated carbon belowground, thereby contributing more directly to SOC accumulation and long-term soil restoration. The establishment of perennial vegetation and semi-natural plant communities can significantly enhance carbon storage while simultaneously improving soil structure, reducing erosion and increasing biological activity. Perennial species allocate a substantial proportion of assimilated carbon below ground, thereby contributing to long-term SOC accumulation and promoting the recovery of ecosystem functions. In addition, the restoration of vegetation cover improves water retention, supports nutrient cycling and creates habitats for soil organisms and other components of biodiversity. Improved soil structure also enhances infiltration capacity and water retention, thereby increasing ecosystem resilience to drought and other climate-related disturbances. These processes contribute to the gradual re-establishment of ecosystem resilience and the provision of regulating ecosystem services.

According to the IPCC AR6 WGIII assessment, land-use change remains one of the principal drivers of AFOLU carbon fluxes globally. Conversely, increases in tree cover and biomass stocks observed in many temperate and boreal regions have contributed to enhanced terrestrial carbon sinks (Nabuurs et al., 2022). In reclaimed post-mining landscapes, the establishment of forests, woodlands and semi-natural grasslands can therefore be regarded as a localized form of ecosystem restoration that contributes to reversing historical carbon losses associated with land degradation and disturbance.

The selection of reclamation techniques strongly influences both the rate and the long-term stability of carbon sequestration. Recent experiences from post-mining reclamation projects indicate that even highly degraded and phytotoxic substrates may be transformed into productive systems through the application of engineered soil substrates incorporating waste-derived materials and organic amendments. Such approaches facilitate vegetation establishment and initiate soil formation processes, which are fundamental for long-term carbon accumulation. The introduction of perennial grass species and semi-natural meadow communities may therefore contribute not only to biomass production but also to increasing soil carbon stocks and restoring ecological functionality.

The importance of such measures is reflected in the IPCC assessment of AFOLU mitigation pathways. According to AR6 WGIII, approximately 30–50% of the AFOLU mitigation potential could be achieved at costs below USD 20 per tonne of CO_2 equivalent, highlighting the high cost-effectiveness of ecosystem restoration approaches. Roe et al. (2021) further emphasize that the effectiveness and feasibility of land-based mitigation measures depend strongly on local environmental conditions, governance frameworks, land ownership patterns and socio-economic context. Consequently, site-specific approaches are essential for maximizing mitigation benefits while minimizing potential trade-offs. Unlike agricultural production systems, where methane (CH_4) and nitrous oxide (N_2O) represent major greenhouse gas emission sources, post-mining land reclamation based on perennial vegetation and ecological restoration is primarily associated with carbon dioxide removal through biomass growth and soil carbon accumulation.

Beyond direct carbon removals, reclaimed post-mining lands may contribute to climate mitigation through several indirect mechanisms. The establishment of permanent vegetation cover reduces soil erosion and limits carbon losses, while improved soil structure and water retention increase ecosystem resilience to droughts, heatwaves and extreme weather events. Furthermore, the productive reuse of marginal and degraded lands alleviates pressure on fertile agricultural areas and reduces the risk of land-use change associated with the expansion of biomass production. Consequently, post-mining land reclamation may transform areas that historically acted as net sources of greenhouse gas emissions into landscapes capable of delivering sustained net carbon removals together with a broad range of ecological benefits. Such multifunctional landscapes simultaneously contribute to climate change mitigation, climate adaptation and the long-term restoration of ecosystem functions, reflecting the integrated approach increasingly promoted within international climate policy (Seddon et al., 2020).

The contribution of post-mining land reclamation to climate objectives is fully aligned with the strategic priorities of the European Union. The European Green Deal identifies ecosystem restoration and carbon sequestration as essential elements for achieving climate neutrality by 2050. Similarly, the EU Soil Strategy for 2030 recognizes healthy soils as a prerequisite for climate resilience, biodiversity protection and sustainable land management. These objectives are further reinforced by the revised LULUCF Regulation (EU) 2018/841, as amended by Regulation (EU) 2023/839, which strengthens the contribution of the land sector to the EU climate target for 2030 by establishing binding targets for net greenhouse gas removals and promoting the enhancement of terrestrial carbon sinks through sustainable land management and ecosystem restoration. More recently, Regulation (EU) 2024/3012 establishing the Carbon Removals and Carbon Farming Certification Framework (CRCF) has created the first European framework supporting carbon farming activities and promoting investments in high-quality carbon removals. Within this context, the restoration of post-mining lands may provide opportunities for integrating reclamation activities with emerging carbon farming schemes, ecosystem restoration programmes and nature-based climate solutions.

The growing policy emphasis on carbon removals also reflects an important shift in climate mitigation strategies. Whereas previous approaches focused predominantly on reducing greenhouse gas emissions, current European climate policy increasingly recognizes the need to enhance long-term biological carbon sinks through ecosystem restoration, improved soil management and sustainable land-use practices. Reclaimed post-mining landscapes represent an underutilized land resource that can contribute to these objectives while avoiding direct competition with productive agricultural land and many natural ecosystems.

From a practical perspective, the climate benefits of post-mining reclamation should therefore be evaluated not only in terms of carbon sequestration rates, but also with regard to the permanence of carbon storage, ecosystem recovery, resilience to climate change and the provision of multiple ecosystem services. Such a holistic perspective is consistent with both the IPCC mitigation framework and the European Union's emerging carbon removal policies.

Overall, the available scientific evidence indicates that appropriately designed reclamation strategies can gradually transform degraded post-mining landscapes from persistent sources of greenhouse gas emissions into long-term carbon sinks. The magnitude of these benefits depends on site-specific environmental conditions, reclamation techniques and subsequent land management; however, the combination of soil restoration, vegetation establishment and sustainable land use creates favourable conditions for long-term carbon accumulation while simultaneously supporting ecosystem recovery and climate resilience.

5.2. Climate change, biodiversity and implications for post mining reclamation

Climate change and biodiversity loss are increasingly recognized as two closely interconnected global environmental crises that mutually reinforce one another. While climate change directly alters environmental conditions and species distributions, biodiversity underpins ecosystem resilience and determines the capacity of natural systems to adapt to changing climatic conditions. Consequently, contemporary approaches to ecosystem restoration increasingly recognize that successful land reclamation must simultaneously contribute to climate change mitigation, climate adaptation and biodiversity conservation rather than addressing these objectives independently (IPBES, 2019; Seddon et al., 2020).

According to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), climate change has become one of the five principal direct drivers of global biodiversity loss, alongside land-use change, direct exploitation of organisms, pollution and invasive alien species (IPBES, 2019). Although land-use change currently remains the dominant driver of biodiversity decline worldwide, the relative importance of climate change is projected to increase substantially during the twenty-first century, interacting with existing anthropogenic pressures and amplifying their ecological consequences (Urban, 2015; Pecl et al., 2017; Wudu et al., 2023). Recent assessments indicate that under higher warming scenarios, climate change may become the predominant driver of biodiversity loss across many terrestrial ecosystems (Shivanna, 2022).

The ecological consequences of climate change extend far beyond changes in average temperature (Markowska & Pierzchala, 2025). Rising temperatures, altered precipitation patterns, increasing frequency of droughts, floods and heatwaves, and the growing occurrence of extreme weather events affect ecosystem structure and functioning at multiple organizational levels. Observed responses include latitudinal and altitudinal shifts in species distributions, changes in species composition and community structure, altered phenological cycles, increasing risks of biological invasions and emerging plant and animal diseases, as well as the degradation of ecosystem services upon which human societies depend (Walther et al., 2002; Urban, 2015; Pecl et al., 2017; Wudu et al., 2023).

Climate change also affects biodiversity through indirect ecological processes that may be more difficult to predict than direct physiological responses (Markowska & Zgórska, 2025). While many impact assessments focus primarily on individual species, increasing evidence suggests that simultaneous exceedance of climatic tolerance thresholds by multiple interacting species may trigger abrupt ecosystem reorganization and the disruption of ecological interactions (Trisos et al., 2020). Such non-linear responses may substantially alter ecosystem functioning, resilience and the capacity to provide regulating ecosystem services, including carbon sequestration, water regulation, soil formation and nutrient cycling. It is important to note that, unlike photovoltaic farms, energy crop cultivation not only reduces the need for fossil fuels but also contributes directly to cooling the ground surface (lowering the ground surface temperature in the summer).

Despite considerable progress in climate impact modelling, substantial uncertainties remain regarding the magnitude, timing and spatial distribution of biodiversity responses to future climate change. These uncertainties arise from differences among climate scenarios, regional environmental conditions, species-specific adaptive capacities and the complexity of ecological interactions (Sunday et al., 2020; Shivanna, 2022). Nevertheless, there is broad scientific consensus that increasing global temperatures will progressively reduce the suitability of many existing habitats while simultaneously creating novel environmental conditions that may favour different ecological communities.

These findings have important implications for ecosystem restoration and land reclamation. Historically, restoration projects frequently aimed to recreate pre-disturbance ecosystem conditions or to approximate historical species composition. However, under rapidly changing climatic conditions, restoring historical ecosystems may no longer be feasible or even desirable in many locations. Instead, increasing attention is being given to the establishment of climate-resilient ecosystems capable of maintaining ecological functions, supporting biodiversity and continuing to provide essential ecosystem services under future environmental conditions (Lindenmayer et al., 2017; Seddon et al., 2020).

This paradigm shift is particularly relevant for post-mining landscapes. Mining activities often result in profound and irreversible alterations of soil profiles, hydrological conditions, geomorphology and habitat characteristics. Consequently, reclaimed post-mining areas rarely possess the environmental conditions necessary for the full reconstruction of pre-mining ecosystems. At the same time, these newly created landscapes offer opportunities to establish novel ecosystems specifically designed to enhance ecological resilience, increase climate adaptation capacity and deliver multiple ecosystem services. From this perspective, reclamation should not be understood solely as a process of repairing environmental damage, but rather as the deliberate creation of multifunctional ecosystems capable of responding to future climatic and socio-economic challenges (Vasiliev, 2022).

The implications of climate change extend beyond the ecological performance of restored ecosystems and directly influence the planning and implementation of reclamation projects. Traditionally, the selection of an appropriate reclamation pathway has been based on a combination of legal, environmental, technical, hydrological, economic and social considerations (Ostręga and Uberman, 2010; Frantál et al., 2012; Ostręga, 2021; Siedlecka and Cieślak, 2022). These include land ownership, spatial planning regulations, geological and engineering conditions, environmental protection requirements, landscape values, expected reclamation costs and the anticipated future use of the site. Under current and projected climate change, however, climate resilience should be regarded as an additional and increasingly important criterion guiding reclamation planning. From this perspective, reclamation should no longer aim exclusively to stabilize degraded land or restore historical land cover. Instead, reclamation strategies should seek to establish ecosystems capable of maintaining their structure, functionality and ecosystem service provision under future climatic conditions. This requires moving beyond static restoration targets towards adaptive management approaches that explicitly recognize the dynamic nature of both ecosystems and climate change (Lindenmayer et al., 2017; Seddon et al., 2020).

The selection of appropriate vegetation represents one of the most critical components of climate-resilient reclamation. Plant communities established during reclamation largely determine the subsequent development of soil properties, carbon accumulation, hydrological regulation, biodiversity recovery and the long-term stability of reclaimed ecosystems. Consequently, species selection should consider not only current site characteristics but also projected changes in temperature, precipitation patterns, drought frequency and the occurrence of extreme weather events over the expected lifetime of the reclaimed ecosystem. Whenever possible, reclamation should prioritize native species that support local ecological networks and contribute to the restoration of regional biodiversity (Markowska & Pierzchała, 2025). Native plant communities generally provide suitable habitats for indigenous fauna, facilitate ecological succession and strengthen ecosystem resilience by maintaining established ecological interactions. However, in highly transformed post-mining environments, the complete reconstruction of historical ecosystems is frequently neither technically feasible nor ecologically realistic. Severe alterations of soil profiles, substrate composition, hydrological conditions and microclimate often create environmental conditions that differ fundamentally from those existing before mining commenced. Climate change further increases this divergence by progressively modifying the environmental conditions under which restored ecosystems will develop.

Consequently, the objective of contemporary reclamation is increasingly shifting from the restoration of historical ecosystem composition towards the establishment of functional ecosystems capable of delivering multiple ecosystem services over the long term. In this context, the concept of ecosystem rehabilitation may provide a more appropriate framework than strict ecological restoration. Whereas restoration seeks to recreate the original ecosystem as closely as possible, rehabilitation focuses on recovering ecological functionality, enhancing ecosystem resilience and restoring the capacity of degraded landscapes to provide environmental, social and economic benefits (Wójcik and Krzaklewski, 2019; Vasiliev, 2022). This functional approach is particularly relevant for post-mining areas, where irreversible alterations frequently preclude the complete re-establishment of pre-disturbance ecological conditions.

Planning reclamation under future climate conditions also requires acknowledging the inherent uncertainty associated with climate projections and the changes in seasonality (Figure 1). Although regional climate models provide increasingly robust estimates of future temperature and precipitation trends, uncertainties remain regarding the magnitude, timing and interaction of future climatic changes (Harris et al., 2006).

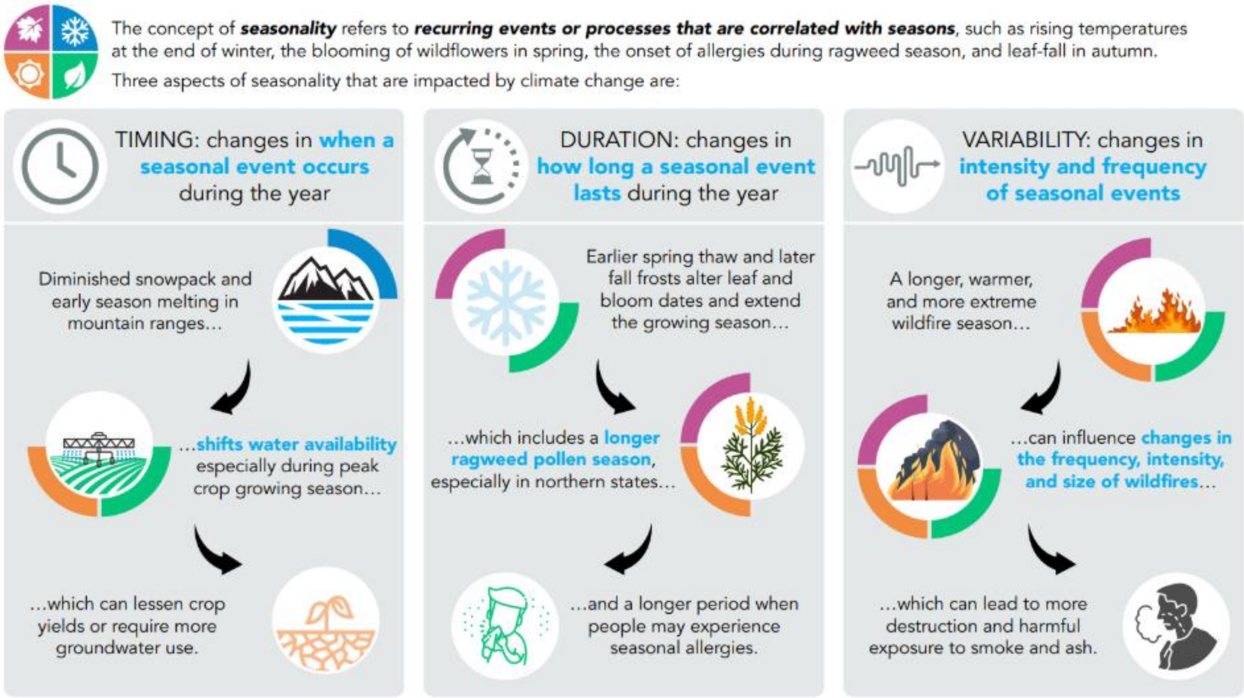

Figure 1. The Impact of Climate Change on Seasonality (EPA, 2021)
Source: EPA (2021) Seasonality and climate change - a review of observed evidence in the United States, https://www.epa.gov/system/files/documents/2021-12/30339_epa_report_climate_change_and_seasonality_v12_release_508.pdf

Rather than attempting to optimize reclamation for a single projected climate scenario, adaptive planning should seek to increase the capacity of reclaimed ecosystems to remain functional across a range of plausible future environmental conditions (Markowska & Zgórska, 2025). This can be achieved through the use of diverse plant communities, species exhibiting broad ecological tolerance, habitat heterogeneity and management approaches that facilitate natural ecological adaptation over time (Markowska & Pierzchała, 2025).

Beyond adaptation, reclamation decisions may themselves influence local climatic conditions (Figure 2). Vegetation cover affects surface albedo, evapotranspiration (ET), soil moisture and local energy balances, thereby influencing microclimatic conditions within reclaimed landscapes (Lamptey et al., 2005). Although these effects are generally localized, they illustrate the reciprocal relationship between land management and climate. Appropriately designed vegetation cover therefore contributes not only to carbon sequestration but also to regulating local temperatures, improving water retention, reducing erosion and enhancing the resilience of reclaimed ecosystems to future climatic stressors.

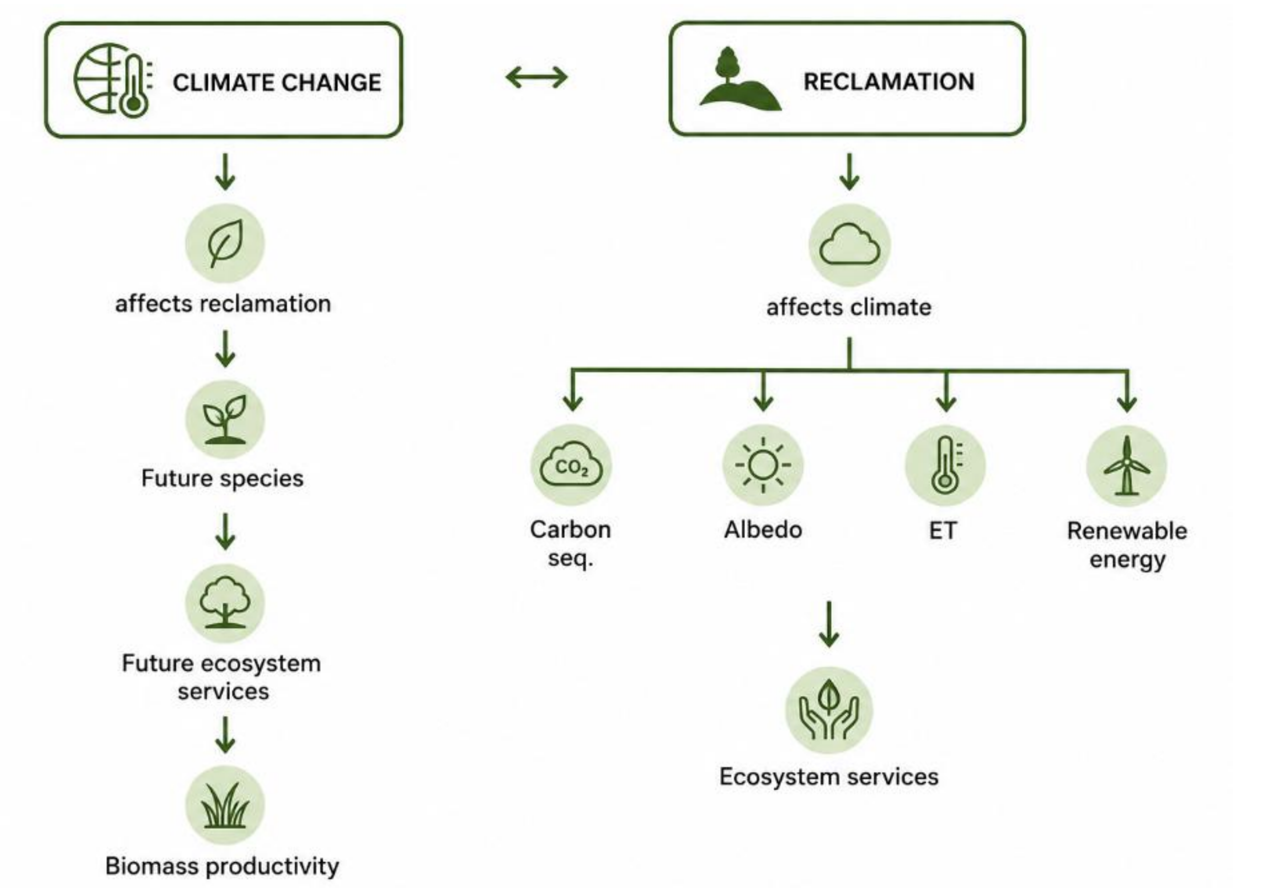

Figure 2. Interconnections between reclamation strategy & climate change
Source: GIG-PIB team own elaboration

Post-mining reclamation should therefore be viewed as a long-term process that combines land restoration with climate change mitigation, biodiversity conservation and climate adaptation. Modern reclamation no longer focuses only on restoring degraded land but also on creating resilient ecosystems that continue to provide ecosystem services under changing environmental conditions. This principle also applies to agricultural reclamation, where sustainable biomass production depends on selecting plant species adapted to future climatic conditions.

5.3. Renewable energy production potential

Beyond their capacity for long-term carbon sequestration and ecosystem restoration, reclaimed post-mining landscapes may also contribute to climate neutrality by supporting the sustainable production of renewable biomass for the energy sector. Among the various reclamation pathways discussed in the previous section, the establishment of perennial biomass production systems represents one of the most promising multifunctional approaches, simultaneously contributing to ecosystem rehabilitation, renewable energy generation and regional decarbonization. Among the various reclamation pathways discussed in the previous section, the establishment of perennial biomass production systems represents one of the most promising multifunctional approaches, simultaneously contributing to ecosystem rehabilitation, renewable energy generation and regional decarbonization. Unlike conventional bioenergy systems established on productive agricultural land, biomass cultivation on reclaimed post-mining sites may increase renewable energy production while largely avoiding direct competition with food production and minimizing additional pressure on natural ecosystems.

According to the IPCC Sixth Assessment Report (AR6 Working Group III), sustainably produced biomass constitutes an important component of the global mitigation portfolio within the Agriculture, Forestry and Other Land Use (AFOLU) sector (Nabuurs et al., 2022; Pathak et al., 2022). Biomass contributes to climate change mitigation through multiple mechanisms, including the substitution of fossil fuels, the accumulation of carbon in vegetation and soils, and the provision of renewable feedstocks for bio-based products. However, the IPCC also emphasizes that the overall climate benefits of bioenergy depend strongly on sustainable land management, life-cycle greenhouse gas emissions and the avoidance of adverse impacts on biodiversity, water resources and food security. These considerations are particularly relevant when selecting appropriate biomass production systems for reclaimed post-mining landscapes.

Compared with conventional agricultural systems, reclaimed mining areas offer several advantages for biomass production. Many post-mining sites are characterized by low agricultural suitability, disturbed soil profiles and various physical or chemical constraints that limit conventional crop cultivation but do not necessarily prevent the establishment of perennial energy crops. Consequently, these landscapes represent an important reserve of underutilized land capable of supporting renewable biomass production without requiring the conversion of forests, semi-natural habitats or high-quality agricultural soils. This approach directly addresses one of the principal sustainability concerns associated with bioenergy development, commonly referred to as the ***food-versus-fuel*** debate (Prasad & Ingle, 2019), by directing biomass production towards marginal and reclaimed lands rather than productive agricultural areas (Roe et al., 2021; Nabuurs et al., 2022).

The suitability of reclaimed post-mining lands for biomass production depends on site-specific environmental conditions, reclamation techniques and long-term management practices. Nevertheless, numerous studies have demonstrated that several perennial species exhibit high tolerance to degraded substrates while simultaneously producing economically viable biomass yields. Among the most extensively investigated species are willow (*Salix spp.*), poplar (*Populus spp.*), miscanthus (*Miscanthus × giganteus*) and switchgrass (*Panicum virgatum*), all of which combine relatively high biomass productivity with low cultivation requirements and the capacity to improve soil quality over time (Lewandowski et al., 2003; Clifton-Brown et al., 2004; Arnoult et al., 2015).

These perennial crops are well suited to land reclamation because they provide both environmental and economic benefits. Their extensive root systems stabilize reconstructed soils, reduce erosion and promote Soil Organic Carbon (SOC) accumulation, while the harvested biomass can be used as a renewable energy source. Once established, they usually require less fertilizer, pesticide application and tillage than annual crops, which lowers management costs and reduces soil disturbance. Unlike conventional crops, perennial energy crops combine biomass production with long-term soil improvement.

The long-term performance of biomass production systems, however, depends not only on current site conditions but also on their capacity to withstand future climatic changes. As discussed in the previous section, increasing temperatures, prolonged droughts, more frequent extreme weather events and changing precipitation patterns are expected to influence biomass productivity across Europe (IPCC, 2022; EEA, 2024). Species selection should therefore consider both current site conditions and future climate projections. Miscanthus and switchgrass generally exhibit relatively high drought tolerance and efficient water use, whereas willow and poplar often perform best where adequate soil moisture can be maintained. Mixed plantations, locally adapted genotypes and diversified production systems can further improve the resilience of reclaimed landscapes.

Although perennial energy crops are the best studied option, other vegetation types may also be suitable depending on local conditions. In reclaimed wetlands and seasonally waterlogged areas, common reed (Phragmites australis) can produce high biomass yields and tolerate variable water conditions. It is suitable for both thermochemical and biological conversion and may simultaneously support wetland restoration, biodiversity and renewable energy production.

Biomass produced on reclaimed post-mining lands can be used in several renewable energy pathways. The most mature and commercially established option is the direct combustion of solid biomass for heat production in district heating systems, industrial facilities and institutional heating plants. In regions undergoing the transition away from coal, locally produced biomass may partially substitute fossil fuels in existing heating infrastructure, thereby reducing greenhouse gas emissions while providing a productive use for reclaimed land.

Another option is combined heat and power (CHP), which produces heat and electricity at the same time. Because waste heat is recovered, CHP systems are considerably more efficient than separate heat and power generation. In former mining regions, biomass-based CHP can diversify local energy supplies, reduce fossil fuel use and improve regional energy security.

A more resource-efficient solution involves the utilization of biomass in combined heat and power (CHP) systems, where heat and electricity are generated simultaneously. CHP installations achieve considerably higher overall energy efficiency than separate heat and power production by utilizing waste heat that would otherwise be lost. The integration of biomass-based CHP into local energy systems may therefore contribute not only to decarbonizing electricity and heating sectors but also to improving energy resilience and reducing dependence on imported fossil fuels. Beyond direct combustion, lignocellulosic biomass can be converted through advanced thermochemical processes, including gasification, pyrolysis and hydrothermal conversion. Gasification produces synthesis gas (syngas), whereas pyrolysis generates bio-oil, combustible gases and biochar. Hydrothermal technologies are particularly suitable for wet biomass. Among these products, biochar has received considerable attention because it links renewable energy production with long-term carbon storage. Applied to reclaimed soils, it increases Soil Organic Carbon (SOC), improves soil structure and water retention, and supports microbial activity. Owing to its high stability, biochar can store carbon for decades or even centuries. Consequently, pyrolysis offers one of the most effective ways to combine renewable energy generation with carbon sequestration and soil restoration. Further details are provided in Section 5.4.

Reclaimed post-mining landscapes can also support biological conversion through anaerobic digestion. Perennial grasses, meadow biomass, common reed and selected agricultural residues may be used to produce biogas. After upgrading, biogas can be converted to biomethane for injection into gas networks or use as a transport fuel. Anaerobic digestion also produces digestate, which supplies organic matter and nutrients that support soil development and vegetation establishment during reclamation.

The wide range of biomass conversion technologies creates opportunities to develop integrated bioenergy value chains that can be adapted to local conditions and available resources. In this approach, biomass production is not considered a standalone agricultural activity but part of a broader circular bioeconomy system. Such systems may include biomass cultivation, harvesting, transport, storage, processing, renewable energy production, and the use of by-products such as digestate and biochar. The cascading use of biomass improves resource efficiency, reduces waste generation, and supports circular economy objectives by maximizing the value obtained from biological resources.

From a regional development perspective, biomass-based value chains can provide significant economic benefits for former mining areas. Activities related to biomass cultivation, harvesting, logistics, processing, and energy generation can contribute to economic diversification and support the development of new bio-based sectors. Although biomass production alone cannot fully compensate for job losses associated with mine closures, it can form an important part of broader regional transition strategies focused on renewable energy development, ecosystem restoration, and the circular bioeconomy.

The successful deployment of biomass production systems on reclaimed land nevertheless requires careful consideration of sustainability criteria. The European Commission and the IPCC emphasize that bioenergy contributes to climate change mitigation only when biomass is produced through sustainable land management practices that maintain soil quality, protect biodiversity and avoid indirect land-use change (European Commission, 2023; Nabuurs et al., 2022). Reclaimed post-mining landscapes are particularly well suited to meeting these requirements because biomass cultivation can be integrated with ecological restoration, carbon sequestration and the rehabilitation of degraded soils, thereby generating multiple environmental benefits beyond renewable energy production alone.

The development of renewable biomass systems on reclaimed post-mining lands is fully consistent with the strategic priorities of the European Union. The European Green Deal promotes the transition towards a climate-neutral economy through ecosystem restoration, renewable energy deployment and sustainable land management. Similarly, the Renewable Energy Directive (RED III) and the REPowerEU Plan emphasize the need to increase the share of renewable energy while strengthening energy security and reducing dependence on fossil fuels. Biomass produced on reclaimed lands may contribute to these objectives by providing sustainable renewable feedstocks without increasing pressure on high-quality agricultural land or natural ecosystems. Consequently, post-mining landscapes should be regarded not only as restored ecosystems but also as strategic components of future low-carbon energy systems capable of supporting regional decarbonization, circular bioeconomy development and climate resilience.

Looking beyond currently established bioenergy pathways, reclaimed post-mining landscapes may also contribute to future negative emission technologies. Biomass produced on reclaimed land could potentially be integrated with Bioenergy with Carbon Capture and Storage (BECCS) systems, in which carbon absorbed during plant growth is captured during energy conversion and permanently stored in geological formations. Although the deployment of BECCS remains limited and depends on technological, economic and regulatory developments, the IPCC identifies BECCS as one of the principal Carbon Dioxide Removal (CDR) options contributing to net-zero and net-negative emission pathways (IPCC, 2022). This illustrates the long-term strategic value of reclaimed post-mining landscapes as providers of sustainable biomass for future climate mitigation systems.

5.4. Circular economy and just transition benefit

The reclamation and productive reuse of post-mining lands offer opportunities that extend beyond environmental restoration and climate change mitigation. By transforming degraded areas into multifunctional landscapes, post-mining land reclamation may support the development of circular bioeconomy models and contribute to the socio-economic transformation of former coal regions. In this context, reclaimed areas should be understood not only as degraded spaces requiring rehabilitation, but also as potential assets capable of generating ecosystem services, supporting renewable energy production and enabling new forms of land-based economic activity (Hamerla et al., 2025; Markowska & Pierzchala, 2025).

Reclaimed post-mining areas can play an important role in regional circular bioeconomy systems because they provide space for biomass production and the reuse of organic waste and secondary materials. Using waste-derived soil amendments, organic residues and other secondary materials during land reclamation is a practical example of circular resource management. These practices reduce waste, improve soil quality and increase carbon storage. As a result, they support both environmental protection and more efficient use of resources.

Agricultural reclamation can also create opportunities for regional biomass value chains based on renewable biological resources. These value chains typically include biomass cultivation, harvesting, logistics, preprocessing, energy conversion and the utilization of secondary products such as digestate or biochar. Combining these activities helps keep materials and energy circulating within the regional economy, reducing the need for external inputs and improving resource efficiency.

At the same time, the socio-economic dimension of post-mining land reuse is particularly relevant in regions undergoing structural transformation away from coal-based economies. Developing biomass-based industries and renewable energy projects can diversify local economies, create new jobs and help communities adapt after mine closures. Although such activities are unlikely to fully offset employment losses in the mining sector, they may provide complementary economic functions and support the gradual restructuring of regional economies towards low-carbon development pathways.

Within this context, post-mining landscapes can be interpreted as important spatial components of Just Transition processes, particularly in coal-dependent regions. European policy frameworks such as the Just Transition Mechanism and the Just Transition Fund (Regulation (EU) 2021/1056) explicitly support investments in land restoration, clean energy development, circular economy initiatives and economic diversification in regions affected by the energy transition. Therefore, productive reuse of reclaimed land is consistent with EU policies promoting climate neutrality, environmental protection and a fair transition for affected regions.

Table 3. Synergies between carbon farming and energy crops in reclaimed post-mining landscapes

Carbon farming benefit	Energy crop / bioenergy system benefit
Soil carbon sequestration	Biomass production
Improved soil structure	Renewable energy feedstock
Reduced erosion and land degradation	Economic viability
Enhanced water retention capacity	Renewable heat, electricity and fuel production
Increased biodiversity and habitat creation	Diversified rural and regional income streams
Organic matter accumulation from amendments and residues	Reduced dependence on fossil fuels and external energy imports
Long-term carbon storage	Potential negative emissions through BECCS

In addition to supporting circular resource use, reclaimed post-mining land may also contribute to climate mitigation through carbon removal. In this context, biomass produced on reclaimed land can be integrated into a multi-layered system of carbon storage pathways, ranging from biological sequestration in vegetation and soils to technologically enhanced removal processes.

The primary mechanism of carbon storage in reclaimed ecosystems is the accumulation of biomass and Soil Organic Carbon (SOC), as discussed in previous sections. This process constitutes the primary mechanism of carbon sequestration in reclaimed ecosystems and forms the basis of carbon farming approaches. Additional technologies may increase both the efficiency and permanence of carbon removal. One example is biochar, which is produced by thermochemical conversion of biomass, most commonly through pyrolysis. When returned to soils, biochar contributes to long-term carbon stabilization due to its high resistance to microbial decomposition. In reclaimed post-mining soils, biochar can also improve physical and chemical properties, including water retention, nutrient availability and aggregate stability. In this way, biochar connects biomass energy systems with long-term soil carbon sequestration.

A further, more advanced pathway is represented by Bioenergy with Carbon Capture and Storage (BECCS). In BECCS systems, carbon absorbed during biomass growth is partially or fully captured during energy conversion processes and subsequently stored in geological formations. As a result, BECCS can generate renewable energy while removing CO_2 from the atmosphere, resulting in net-negative emissions under appropriate system conditions. Although BECCS is still used only on a limited scale because of technological, economic and infrastructure challenges, it is consistently identified in IPCC mitigation scenarios as one of the key Carbon Dioxide Removal (CDR) options required to achieve global net-zero and net-negative emission pathways (IPCC, 2022). In this context, reclaimed post-mining landscapes may be viewed as potential upstream components of future BECCS systems, providing sustainably sourced biomass feedstocks without competing with food production or high-value land uses. Although this approach is still largely theoretical, it illustrates how reclaimed land could support future carbon removal systems.

The interaction between SOC enhancement, biochar application and potential BECCS deployment illustrates a hierarchical structure of carbon removal options (Figure 3). Current research increasingly suggests that no single carbon removal technology will be sufficient. Instead, achieving climate neutrality will require combining several complementary approaches.

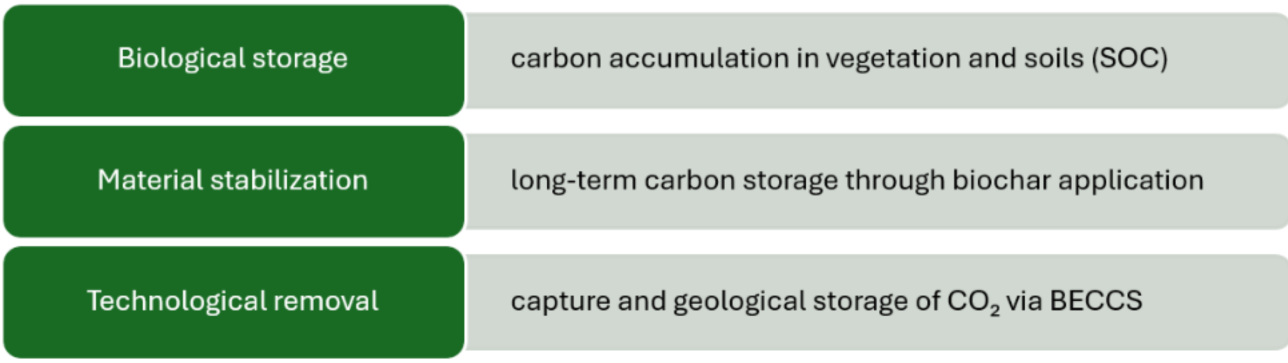

Figure 3. Interaction between SOC enhancement, biochar application and potential BECCS deployment
Source: GIG-PIB own elaboration

From a policy perspective, these developments are increasingly reflected in EU legislation. The European Green Deal aims to achieve climate neutrality by 2050, while the EU Soil Strategy for 2030 promotes soil restoration and increased soil carbon stocks. In addition, the Carbon Removals and Carbon Farming Certification Framework (CRCF; Regulation (EU) 2024/3012) establishes rules for certifying carbon removals, including soil carbon sequestration and carbon farming.

Reclaimed post-mining landscapes may therefore become eligible sites for verified carbon removal activities, particularly where biomass production, soil restoration and long-term carbon storage are combined in integrated land-use systems. This may improve the economic viability of large-scale reclamation by linking ecological restoration with renewable energy and emerging carbon market.

6. Best Practice Guidelines

6.1. Assessment Framework

The case studies were assessed according to the methodological framework defined in Chapter 3. The assessment was not intended to rank the practices, but to ensure a consistent interpretation of their relevance for post-mining land reclamation, biomass production and carbon farming. Each practice was analysed through three dimensions: **usefulness, environmental safety and carbon farming component**. Usefulness refers to vegetation establishment, soil stabilisation, biomass production or improvement of soil functions. Environmental safety concerns the risk of contaminant transfer to biomass, water, ash, digestate or products. The carbon farming component refers to evidence of SOC increase, carbon balance or durable reduction of carbon losses from the soil–plant system.

The practices were described using a common structure covering site context, objective, applied intervention, benefits, success factors, limitations, transferability and final assessment. Where data on SOC, baseline conditions, sampling depth, bulk density or monitoring period were missing, the practice was not classified as verified carbon farming. Instead, it was interpreted as a reclamation practice, a biomass production practice with carbon farming potential, or a practice requiring further validation.

6.2. Case Studies: Success and Failure Examples

6.2.1. Greece: Robinia pseudoacacia for mine land reclamation and development of apiculture

Description and objectives

This practice concerns the establishment of black locust (*Robinia pseudoacacia*) stands on post-lignite mining lands in the Western Macedonia Lignite Basin. It represents a biological reclamation approach aimed at the rapid restoration of vegetation cover, erosion control, and the recovery of ecological and productive functions on degraded mine substrates.

Plantations were established on spoil heaps characterized by low agricultural suitability, disturbed soil structure, and elevated erosion risk. As a result of long-term reclamation activities, the largest black locust afforestation complex in Greece was created, covering more than 15,000 acres. This case represents an example of large-scale reclamation conducted in a landscape transformed by lignite mining operations and overburden dump formation (Papadopoulos et al., 2018). The distribution of afforested areas on spoil heaps is presented in Figure 4.

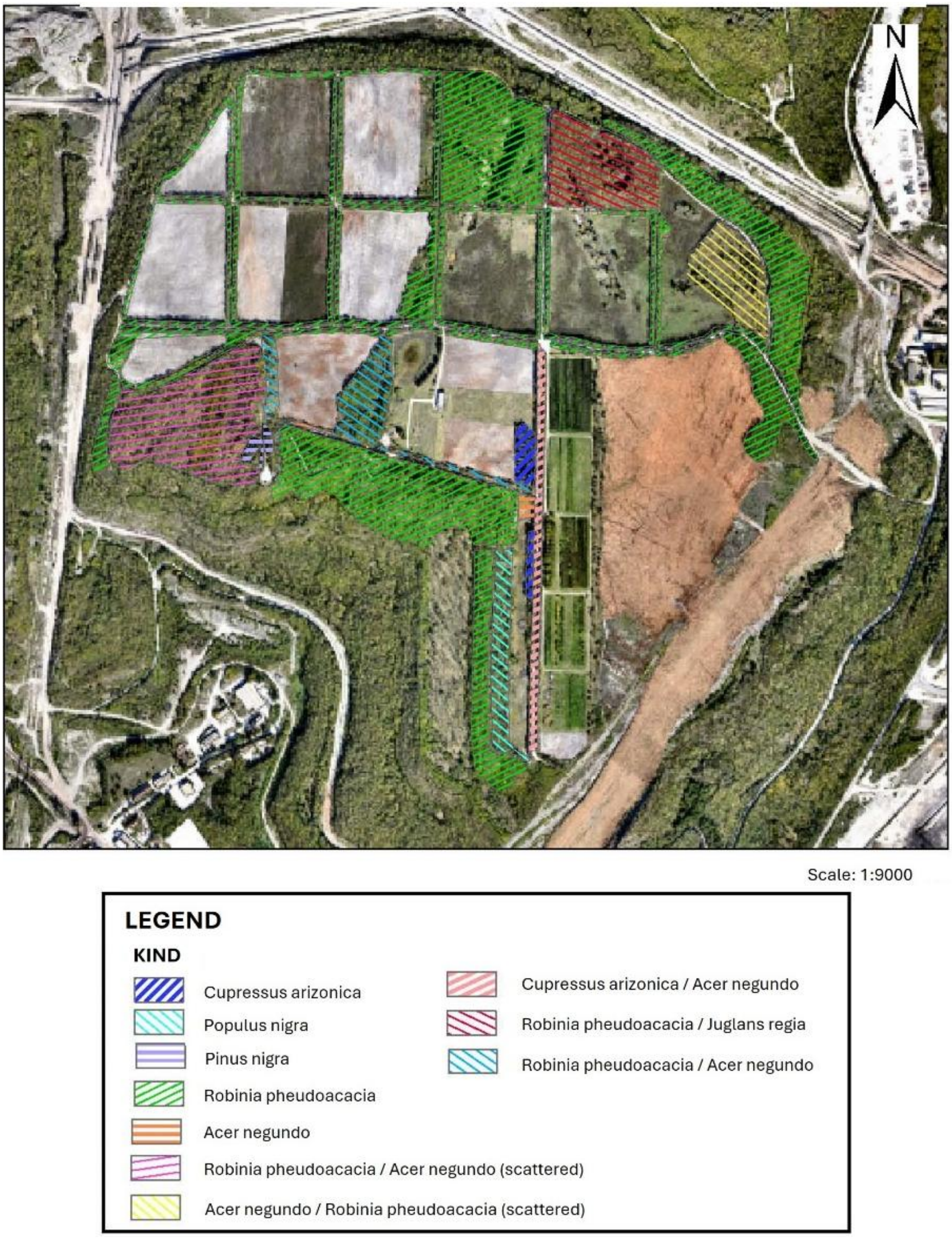

Figure 4. Forest species of old plantations in the mining waste dump of the orchard, Lignite Centre of Western Macedonia of Greece.

The primary objective of the implementation was to restore vegetation cover on land degraded by open-pit mining, reduce erosion processes, and create new environmental and economic functions following the cessation of mining operations. An additional objective was to increase carbon sequestration potential and support the development of local apiculture through the utilization of the high nectar-producing value of black locust.

Black locust (Robinia pseudoacacia) was used for reclamation due to its rapid growth, high seedling survival rate (approximately 90%), and ability to thrive on poor and disturbed soils. The species acts as a pioneer tree, enabling rapid revegetation of spoil heaps and stabilization of soil surfaces. In many locations, black locust was combined with other tree and shrub species to increase biodiversity and improve the landscape functions of reclaimed areas.

Environmental and carbon farming benefits

The practice provides both productive and ecosystem service functions. In addition to its afforestation role, black locust can supply fuelwood and, during its flowering period, support apiculture through nectar and pollen production. The extensive afforested areas created a valuable forage resource for beekeeping. It is estimated that approximately 1,500 ha of black locust forests can support around 1,000 bee colonies and enable the production of 50–70 tonnes of honey annually. Black locust provides nectar and pollen during the late spring period, significantly increasing forage availability for pollinators (Papadopoulos et al., 2018). As a result, this case represents an example of post-mining land management that combines ecological stabilization with a local bioeconomy function.

The primary environmental benefit of this practice is the rapid and effective restoration of vegetation cover on degraded post-mining land. Black locust is recognized as a species particularly suitable for the reclamation of poor and degraded soils and as a fast-growing tree well adapted for lignite mine reclamation, afforestation, and erosion control.

Its importance is mainly associated with soil surface stabilization, reduction of erosion processes, and restoration of vegetation cover. These effects constitute an important prerequisite for long-term soil regeneration, particularly in post-mining areas where exposed substrates are vulnerable to surface runoff, erosion, and the continued loss of fine soil fractions.

The availability of nectar and pollen during the late spring season supports insect populations, especially honey bees, and may strengthen the development of local beekeeping activities. From the perspective of good practice, this example is important because it goes beyond landscape enhancement and demonstrates a functional approach to post-mining land use that combines afforestation, erosion control, and a measurable provisioning ecosystem service.

From an environmental safety perspective, however, the practice requires careful assessment. The main risk is ecological rather than toxicological. Black locust is considered one of the invasive alien tree species in Europe because its root suckering capacity enables it to spread into adjacent areas and displace native species. Consequently, this practice should not be regarded as a universal or entirely environmentally neutral solution. It is an effective reclamation tool under specific degraded-land conditions; however, its application requires monitoring of its expansion and assessment of its potential impacts on native vegetation.

The carbon farming aspect remains only potential in the analysed material. The establishment of woody vegetation may contribute to carbon storage in biomass, erosion reduction, and the gradual accumulation of organic matter in soils. However, no data were provided regarding soil organic carbon (SOC), soil organic matter (SOM), baseline carbon content, sampling depth, soil bulk density, carbon stocks, or long-term carbon balance. Therefore, this case cannot be classified as a verified carbon farming practice. A more accurate interpretation is to consider it a reclamation and ecosystem restoration practice with potential relevance for carbon farming, provided that future monitoring studies confirm increases in carbon stocks.

Success factors and limitations

The success of this practice is primarily linked to the biological characteristics of black locust, including high seedling survival, tolerance to poor soils, rapid growth, low maintenance requirements, and the ability to reduce erosion. These attributes make the species particularly suitable where the main reclamation objective is the rapid establishment of stable tree cover on poor post-mining substrates. The scale of implementation in Western Macedonia also demonstrates the practical applicability of this method under lignite mine reclamation conditions. An additional factor contributing to the success of the project was the implementation of reclamation on large, contiguous areas.

The transferability of this practice to other regions is conditional. The example may provide inspiration for the reclamation of severely degraded post-mining land where rapid soil stabilization and erosion control are priority objectives, especially when ecosystem services such as beekeeping are intended to form part of the future land-use strategy. However, it should not be transferred indiscriminately to areas of high conservation value, sensitive habitats, or locations where controlling the spread of an alien species is not feasible. The same characteristic that supports colonization of degraded soils, high competitiveness and expansion capacity may constitute a significant limitation where biodiversity conservation is the primary objective.

Limitations

The most important limitation is the potential invasiveness of black locust and its capacity to displace native species. In addition, honey production is highly dependent on weather conditions, which may result in considerable fluctuations in nectar flow and productivity between seasons. The practice is well documented as a method for vegetation restoration and erosion control, and its honey production potential has been quantified. However, information is lacking regarding changes in SOC content, biological soil regeneration, pollutant uptake by plants, fuelwood quality, the safety of ash utilization, honey safety, and the results of long-term monitoring.

Final assessment

This case is an example of an effective practice of mining land reclamation, the main objectives of which are the rapid restoration of vegetation cover, the reduction of erosion and the restoration of productive ecosystem functions. The added value of this practice comes from combining ecological stability with the potential of honey production.

However, this solution is not without risk. The alien and potentially expansive nature of the acacia robinia requires proper ecological control and careful selection of locations. In the absence of data on changes in soil organic carbon content, the practice should be interpreted as a good restoration practice with ecosystem benefits and potential relevance for carbon farming, and not as a proven practice of carbon farming.

Final classification: Good post-mining land reclamation practice providing ecosystem service benefits and having potential relevance for carbon farming; it is not a verified carbon farming practice.

6.2.2. Greece: Experimental fruit orchards on rehabilitated old mine soils

Description and objectives

The case concerns the productive reuse of rehabilitated old mine soils in the West Macedonia Lignite Centre in Northern Greece. The study was carried out in a post-mining area affected by more than five decades of lignite production in the Ptolemais lignite-bearing basin. The mining activity significantly modified environmental conditions in the wider area due to the scale of surface mining and the applied extraction method. In this context, fruit cultivation was tested not as a conventional agricultural activity, but as a higher-order rehabilitation pathway, moving beyond basic ecosystem recovery towards productive land reuse (Papadopoulos et al., 2018).

The orchard was located on a reclaimed waste dump in an area that had previously been rehabilitated and cultivated for more than a decade with cereal crops. This is important methodologically: the case does not represent direct planting on raw mine spoil, but the use of a post-mining substrate that had already undergone a first stage of agricultural rehabilitation. The study area was described as a 5 ha orchard and vineyard established by the Public Power Corporation SA to evaluate the adaptability of fruit tree species in this specific post-mining environment (Papadopoulos et al., 2018).

The terrain had several features favourable for orchard management. Slopes varied from nearly level to gentle, which facilitated farm operations and supported both cold air drainage and surface water drainage. These conditions are relevant because fruit crops are sensitive not only to soil quality but also to local microclimatic conditions, frost exposure and water movement. In post-mining landscapes, such terrain-related factors can determine whether agricultural rehabilitation remains technically manageable over the long term (Papadopoulos et al., 2018).

Soil conditions were mixed. Laboratory analyses characterised the soil as alkaline, with normal electrical conductivity values. The particle-size distribution ranged from moderately coarse to fine, with low clay percentages, which was described as typical for recently formed soils. Organic matter content ranged from medium to high, partly because low-calorific lignite had been dumped at the site; however, the normal decrease in organic matter content with depth, typical of agricultural soils, was not observed. The spoil-derived substrate also had high $CaCO_3$ content, high cation exchange capacity and sufficient exchangeable K^+, Ca^{2+} and Mg^{2+}, while phosphorus was below the accepted availability threshold of 20 mg/kg and zinc deficiency was identified. These parameters show that the site had partial agronomic potential but still required targeted fertility management (Papadopoulos et al., 2018). Localization of experimental fruit orchards is presented in Figure 5.

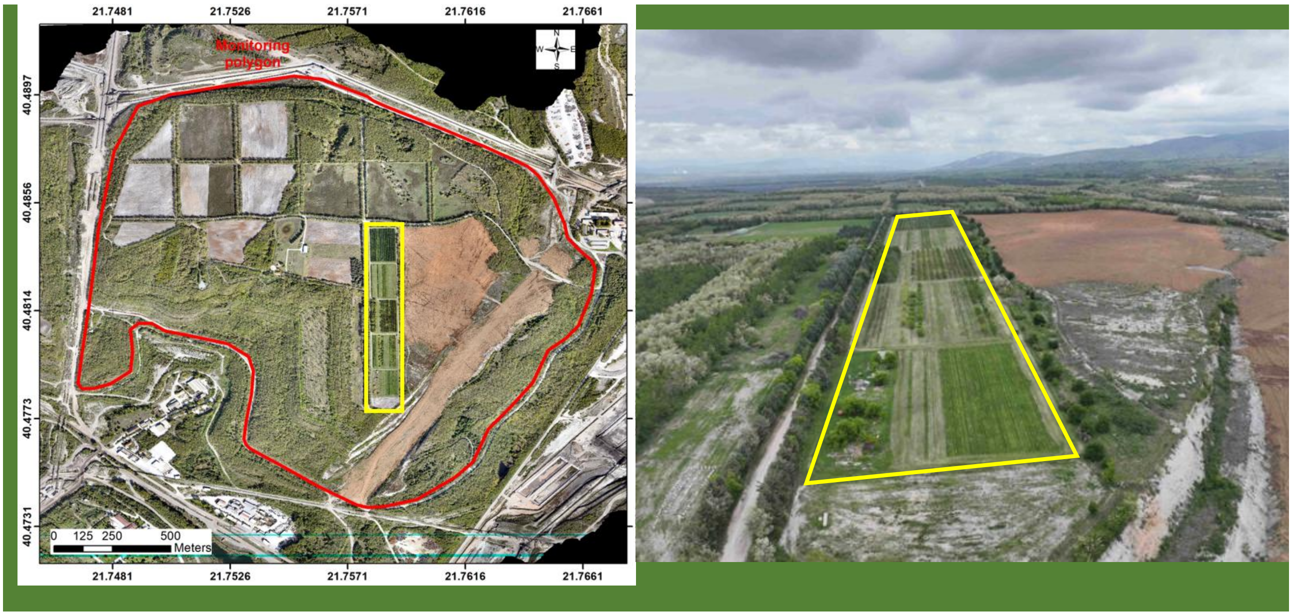

Figure 5. Location of the experimental fruit orchards in Western Macedonia, Greece, and view of the study area.

The primary objective of the practice was to evaluate whether rehabilitated mine soils could support perennial fruit production after lignite extraction and initial land rehabilitation. The broader purpose of rehabilitation in the West Macedonia post-mining area was defined as recovery of nature and ecosystems and creation of a self-sustaining land surface, but the study explicitly extended this aim towards productive uses, including agricultural crops and other economic land-use options. This case is therefore more demanding than basic revegetation or biomass production. Fruit crops require adequate soil fertility, drainage, disease control, frost resilience and food-safety assurance. The practice tests whether post-mining land can be restored to a level that allows not only plant establishment but also production of market-relevant or consumable crops. The study assessed adaptation through yield, blossom set, disease incidence and survival rates, using adjacent control orchards as a benchmark (Papadopoulos et al., 2018)

The applied practice consisted of establishing a diversified experimental orchard and vineyard on rehabilitated old mine soils. In 2001, the planting scheme included 15 apple varieties, 9 pear varieties, 10 cherry varieties, 3 walnut varieties, 9 peach varieties, 1 nectarine variety, 1 plum variety, 4 grapevine varieties, 1 quince variety, 1 jujube variety, 1 raspberry, 1 gooseberry and 2 persimmon varieties. The range of tested species and cultivars makes this case especially valuable because it does not treat orchard cultivation as a single homogeneous practice; instead, it evaluates differential adaptation of fruit crops under post-mining soil and climate constraints.

The management programme was conducted with horticultural support from the Technological Education Institute of West Macedonia. It included fertilisation based on soil tests or leaf tissue analyses, staking of young trees, pruning and pesticide applications. This confirms that the practice should be understood as managed agricultural rehabilitation, not passive revegetation. The observed results therefore reflect both the potential of selected species and the effect of systematic orchard management under post-mining conditions (Papadopoulos et al., 2018).

Environmental and carbon farming benefits

The case demonstrates that selected fruit crops can be productive on rehabilitated mine soils, although not at the level of conventional control orchards. During the 2010–2014 growing periods, observations covered tree health, blossom, relative yield, soil characteristics, farm management and rehabilitation-related problems. Grapevine, cherry, walnut, apple and jujube showed the best adaptation, while fruit yield on rehabilitated soils did not exceed 60% of control-orchard yield. The detailed crop-response table confirms that adaptation was strongly species- and cultivar-dependent. Several apple cultivars, cherry cultivars, walnuts and grapevines were rated as well adapted, with good growth and 50–60% of control-orchard yield. Other crops showed only medium growth or poor adaptation. This is the central practical lesson of the case: rehabilitated mine soils may support fruit production, but only after crop screening and cultivar-level selection (Papadopoulos et al., 2018).).

The case includes a relevant food-safety result. Heavy-metal tests in fruit did not show significant differences compared with fruit from local markets. This finding is important because, in post-mining agricultural reuse, product safety cannot be inferred from tree growth or yield alone. The safety of edible crops requires direct testing of harvested products, especially where mining substrates may contain trace elements (Papadopoulos et al., 2018).

The soil chemistry helps explain why metal transfer to fruit was considered limited in this case. Co and Ni concentrations were below toxicity levels, and the probability of their transfer into the food chain was assessed as very low because the high soil pH reduces metal mobility and availability to plants. This safety interpretation is site-specific. It should not be generalised to acidic or differently contaminated post-mining soils without product testing (Papadopoulos et al., 2018).

The case has potential relevance to carbon farming because it introduces perennial woody vegetation on rehabilitated mine soils and may contribute to long-term soil cover, root biomass, organic matter inputs and erosion reduction. However, no direct data are provided on SOC stock, baseline soil carbon, bulk density, sampling depth, annual carbon inputs, soil respiration or carbon balance. The case therefore cannot be classified as a verified carbon farming practice. Its carbon farming relevance is indirect and conditional. The orchard may support gradual soil functional development and long-term vegetative cover, but the publication evaluates crop adaptation rather than carbon sequestration. Without these data, the case should be treated as an agricultural rehabilitation practice with potential carbon farming relevance, not as a carbon farming case in the strict sense.

Success factors and limitations

The main success factor is precise crop and cultivar selection. Apples, cherries, walnuts, grapevines and jujube performed better than peach, persimmon, raspberry, pear and quince. The less successful crops were limited by different factors: peach and persimmon were sensitive to late spring frosts, raspberry probably failed due to high soil pH, while pear and quince were affected by severe fire blight, leading to tree loss after ten years, with exceptions for selected varieties. A second success factor is active fertility management. The authors concluded that fruit crops on rehabilitated soils may require fertiliser rates above normal agricultural dressings and that further investigation is needed on soil amendments such as biosolids, mulch and compost to improve crop growth and yield. This indicates that the practice is not a low-input rehabilitation model; it requires diagnosis, amendments and professional orchard management (Papadopoulos et al., 2018).

The practice is transferable as a pilot model for controlled agricultural rehabilitation, not as a universal recommendation to establish orchards on post-mining land. Its transferable elements are the methodological sequence: use of land after initial rehabilitation, soil testing, diversified cultivar trials, comparison with control orchards, professional horticultural management and fruit-safety testing. Transfer to other sites would require comparable or locally validated conditions: manageable slopes, adequate drainage, controlled soil fertility, appropriate pH, low mobility of harmful elements, acceptable frost exposure, disease management capacity and repeated product-safety testing. The case should not be transferred to raw mine spoil, acidic substrates, poorly drained land or sites with untested contamination profiles.

The case has several limitations. Fruit yields remained below those of control orchards. Adaptation varied strongly across species and cultivars. Some crops failed or showed severe constraints linked to frost, pH or disease. The available material does not provide a full quantitative dataset for metal concentrations in fruits, a complete economic analysis, irrigation data, long-term food-safety monitoring or SOC measurements.

The absence of SOC data is decisive for carbon farming interpretation. The orchard is a relevant rehabilitation and agricultural reuse case, but it cannot be classified as a verified carbon farming practice without soil carbon monitoring.

Final assessment

The experimental orchard at the West Macedonia Lignite Centre is a good example of selective agricultural rehabilitation on post-mining land. Its main value lies in showing that rehabilitated mine soils can support some fruit crops when the site has already undergone initial rehabilitation, when management is systematic and when crop selection is based on species- and cultivar-specific adaptation. The case is particularly useful because it documents both positive and negative crop responses, avoiding an overly general claim that orchard cultivation is suitable for all rehabilitated mine soils.

The practice also demonstrates that food production on post-mining land requires product-safety verification. The reported lack of significant differences in heavy-metal content between fruits from the rehabilitated site and local market fruits strengthens the case, but does not remove the need for continued monitoring under other site conditions.

Final classification: Selective agricultural rehabilitation good practice with documented crop-specific performance and partial food-safety verification; potential carbon farming relevance.

6.2.3. Greece: Aromatic plant cultivation on reclaimed lignite mine land

Description and objectives

The practice concerns the cultivation of aromatic plants on the reclaimed areas of the Amyntaio lignite mine, located in the Florina prefecture in Western Macedonia (Greece). The area of the mine covers about 61.83 km², while the analyzed plantings were located on a reclaimed internal dump with an area of about 80.5 ha.

The cultivation of aromatic plants is part of the activities carried out in the post-mining areas of Western Macedonia. In the Amyntaio area, rosemary (Rosmarinus officinalis), lavender (Lavandula spp.), oregano (Origanum vulgare) and sage (Salvia officinalis) are grown. The distribution of plantations includes separate sectors for individual species, and the area has been subject to environmental monitoring since at least 2020. The cultivation of aromatic plants has been developed since 2020 and includes 20,000 plants of oregano (4.6 ha), 5000 lavender (2.74 ha), 4000 rosemary (1.62 ha), and 12,000 sage (0.99 ha) (Figure 6).

The Amyntaio mine area has been included in the Thematic Ecological Study (TES), which includes an inventory of flora, habitat types and the occurrence of protected and alien species. The results of the study indicate that the areas intended for reclamation function in an environment with diverse natural values, which requires taking into account aspects of biodiversity protection when planning new forms of development of post-mining land.

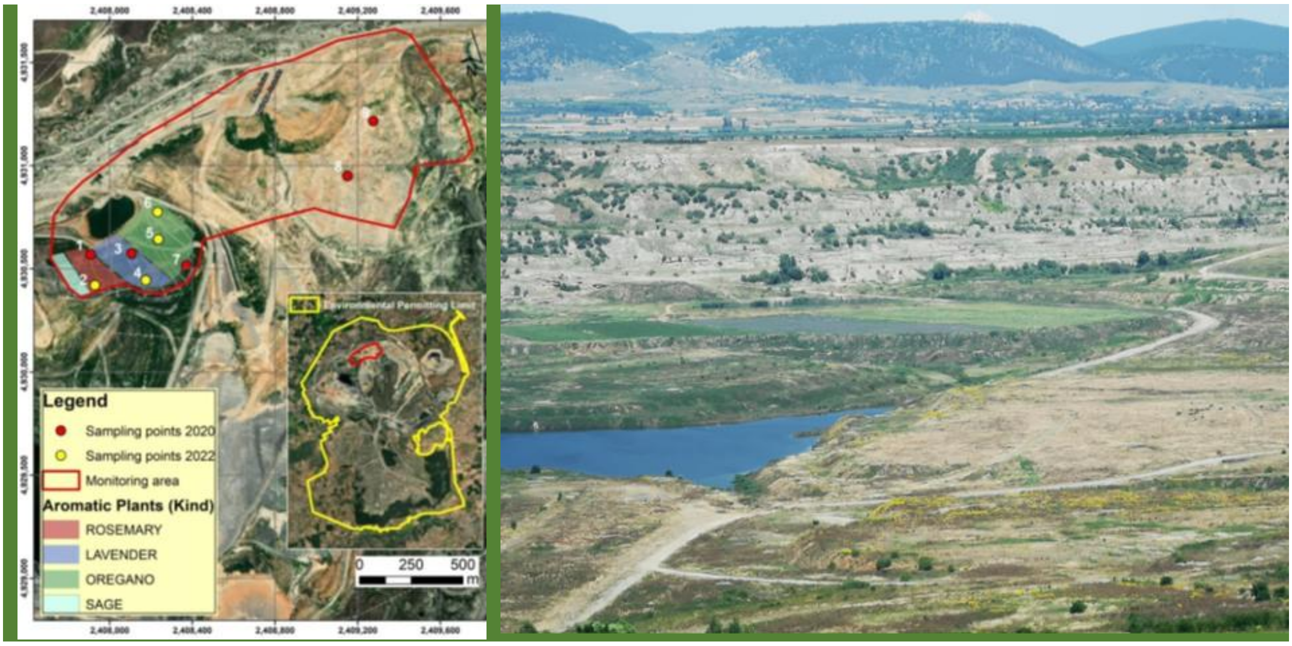

Figure 6. The aromatic plants area in Western Macedonia, Greece.

The aim of the internship is to develop a production, non-agricultural and food method of developing reclaimed areas after lignite mining through the cultivation of aromatic plants.

The practice involves the cultivation of four species of aromatic plants: oregano, lavender, rosemary and sage in the reclaimed inner dump of the Amyntaio lignite mine. Individual species are grown in separate sectors.

The available information allows to define the practice as a full-scale cultivation of aromatic plants on reclaimed post-mining areas, but not as a fully documented agrotechnical protocol.

Environmental and carbon farming benefits

The main value of this practice lies in testing a productive and relatively non-invasive approach to the management of land reclaimed following lignite mining. Aromatic plants may be particularly useful in such areas, as they enable economic value to be generated without the need for high biomass production, high soil fertility or direct use in the food chain.

The practical significance is further enhanced by the scale of the project. Data on area and plant numbers indicate that oregano accounts for the largest share of cultivation, followed by lavender, rosemary and sage. This may indicate the ability of individual species to adapt to the various microenvironmental conditions found on the spoil tip, such as humidity, slope exposure, substrate depth and variability in soil properties.

The environmental safety profile of this practice cannot currently be fully assessed due to a lack of relevant data. Aromatic plants may represent a relatively cautious approach to the management of post-mining land, as they are used primarily for herbal, aromatic and industrial purposes.

The significance of this practice for carbon farming has not yet been confirmed. The cultivation of aromatic plants may contribute to maintaining vegetation cover, reducing erosion, and gradually stabilizing the biological properties of reclaimed soils, particularly in the case of perennial species or those used for several years. These effects may support the restoration of soil functions and create conditions conducive to carbon sequestration.

Success factors and limitations

The success of this practice was possible thanks to the earlier reclamation and stabilization of the dump on which aromatic plantations were established. This means that the results obtained should not be directly related to unreclaimed post-mining areas. It is also important to properly select species for local habitat conditions, including soil properties, water conditions and the level of soil pollution. An additional element determining the success of the project is the monitoring of production quality, including both the assessment of soil parameters and the control of the quality and safety of the obtained biomass, including herbal raw materials and essential oils.

The practice can be transferred primarily as a model of diverse, non-food use of reclaimed post-mining areas. The most transferable elements include the use of previously reclaimed areas, the cultivation of several species of aromatic plants, the spatial separation of individual species and the possibility of integrating production with environmental monitoring. However, moving the solution to other areas requires local validation. The practice should not be copied without taking into account differences in soil pH, water availability, pollutant mobility, climatic conditions and ecological constraints. The intended destination of the final product is particularly important, as a different level of safety requirements applies to industrial, cosmetic, herbal or consumer applications.

The success of this practice was possible thanks to the earlier reclamation and stabilization of the dump on which aromatic plantations were established. This means that the results obtained should not be directly related to unreclaimed post-mining areas. It is also important to properly select species for local habitat conditions, including soil properties, water conditions and the level of soil pollution. An additional element determining the success of the project is the monitoring of production quality, including both the assessment of soil parameters and the control of the quality and safety of the obtained biomass, including herbal raw materials and essential oils.

However, moving the solution to other areas requires local validation. The practice should not be copied without taking into account differences in soil pH, water availability, pollutant mobility, climatic conditions and ecological constraints. The intended destination of the final product is particularly important, as a different level of safety requirements applies to industrial, cosmetic, herbal or consumer applications.

The most important limitation is the lack of data on crop efficiency and product safety. The materials provided identify the location, species and scale of the project, but do not include information on plant survival, yields, biomass quality, essential oil yields, soil quality improvements, contaminant uptake, product safety or changes in SOC content.

The second limitation is the lack of information on how to cultivate crops. No data were provided on irrigation, fertilization, use of soil additives, plant protection, harvesting, post-harvest processing or economic viability of the project.

The third limitation is the lack of data to assess the impact on carbon sequestration. Although crops can contribute to increasing plant cover and stabilizing the substrate, there is currently no evidence of carbon accumulation. To this end, studies involving SOC resources, sampling depth, soil volumetric density and cyclical measurements over time would be necessary.

Final assessment

The case of aromatic plant cultivation in Amyntaio provides an inspiring example of the productive use of reclaimed land after lignite mining. Its greatest value is the departure from simple greening of post-mining land in favor of diversified crop production of a non-food nature.

However, the practice should be interpreted with caution at this stage. This is a potentially valuable solution for land use restoration and diversification, but the available materials do not yet document production results, product safety, soil quality improvements, or carbon accumulation effects. Therefore, the practice should be treated as a solution in the validation stage, and not as a proven example of carbon farming.

Final classification: A practice of production reclamation that is at the validation stage; relevant for diverse, non-food management of reclaimed areas after lignite mining; of potential importance for coal farming.

6.2.4. Greece: Energy crops - cardoon biomass supply chain in depleted surface mines

Description and objectives

This case concerns the proposed cultivation of cardoon (Cynara cardunculus L.) as a perennial energy crop on reclaimed lignite mine land in the Ptolemaida region of Western Macedonia, Greece. The land belongs to the Public Power Corporation (PPC) and forms part of a broader post-mining restoration strategy following the progressive phase-out of lignite extraction. According to the restoration scenario developed by Iliadis et al. (2018), approximately 37% of the rehabilitated mining area, corresponding to 5,471 ha, could be allocated to energy-crop cultivation.

The case represents an integrated post-mining land-use model rather than a conventional agricultural production system. It combines land reclamation objectives with biomass production and renewable energy generation, supporting the economic transition of a region historically dependent on lignite mining (Iliadis et al., 2018).

The primary objective was to evaluate whether cardoon biomass produced on restored mine land could provide a reliable feedstock for district heating systems, biomass-fired power generation, or co-firing with lignite in existing PPC energy facilities. The assessment covered the entire biomass value chain, including cultivation, harvesting, transport, storage, and final energy utilisation, with particular emphasis on technical and economic feasibility (Iliadis et al., 2018).

The analysed practice is based on large-scale cultivation of cardoon on reclaimed post-mining land. Cardoon was selected because it is a perennial Mediterranean species characterised by low input requirements, tolerance to drought, extensive rooting depth, and the capacity to produce significant quantities of lignocellulosic biomass under semi-arid conditions (Fernández & Curt, 2006; Grammelis et al., 2008; Mauromicale et al., 2014).

The species has been widely investigated as an energy crop in Southern Europe due to its adaptation to marginal environments, modest fertiliser requirements, and ability to maintain productivity over multiple years (Fernández & Curt, 2006; Mauromicale et al., 2014). Long-term trials have demonstrated its suitability for biomass production in Mediterranean regions and its potential contribution to renewable energy supply chains (Gominho et al., 2014; Grammelis et al., 2008).

In the Ptolemaida scenario, the cultivation area was assumed to cover 5,471 ha, with a planting density of approximately 15,000 plants per hectare. Expected dry biomass production was estimated at 20 t ha^{-1}, with a harvest moisture content of 7–10%, a gross calorific value of approximately 18 GJ t^{-1} and a cultivation cycle of ten years (Iliadis et al., 2018). Under these assumptions, annual biomass production was estimated at 109,420 t, corresponding to an energy potential of approximately 1,969.6 TJ (Iliadis et al., 2018).

Environmental and carbon farming benefits

The principal value of the practice lies in providing a productive and economically relevant after-use for land previously occupied by lignite mining. By integrating biomass production with land restoration, the approach offers a potential pathway for supporting the broader energy transition in coal-dependent regions. According to Iliadis et al. (2018), the estimated biomass resource could contribute to district heating networks, provide approximately 5% supplementary fuel input to a nearby PPC power station, or support a dedicated biomass combustion plant with an installed capacity of approximately 30–35 MW.

An additional strength of the case is its system-wide perspective. Rather than focusing exclusively on crop productivity, the assessment evaluated the complete biomass supply chain, including harvesting, transport and storage operations. The most cost-effective configuration involved the use of dedicated machinery, contracted personnel and bulk storage in protected open windrows. Under these assumptions, the total cultivation and logistics cost was estimated at approximately €30.45 per tonne of biomass (Iliadis et al., 2018).

Available evidence suggests that reclaimed PPC mining areas can support agricultural production comparable to that achieved in surrounding agricultural regions. Previous experience on rehabilitated deposits showed that crops grown on restored mine soils achieved acceptable productivity levels and displayed nutrient and trace-element concentrations broadly similar to those observed in conventional agricultural soils (Iliadis et al., 2018).

However, the available documentation does not provide detailed information on biomass contamination, ash quality, trace-element transfer, combustion by-products, or long-term environmental monitoring. Consequently, while the practice appears technically feasible from a biomass production perspective, additional assessment would be required before large-scale operational deployment, particularly regarding biomass quality and residue management.

The case cannot currently be classified as a verified carbon farming practice. Although perennial crops such as cardoon may contribute to erosion control, soil protection, below-ground biomass accumulation and reduced fossil-fuel dependence, no direct measurements of soil organic carbon (SOC), soil organic matter (SOM), greenhouse-gas balances, below-ground carbon stocks or long-term carbon sequestration were reported (Iliadis et al., 2018). Nevertheless, literature indicates that cardoon can perform well on marginal land with limited external inputs and may contribute indirectly to climate-change mitigation through renewable energy production and partial substitution of fossil fuels (Fernández & Curt, 2006; Grammelis et al., 2008; Mauromicale et al., 2014). Therefore, the practice should be regarded primarily as a bioenergy and post-mining land-restoration measure with potential climate benefits rather than a demonstrated carbon sequestration approach.

Success factors and limitations

The first prerequisite for successful implementation is the existence of a complete biomass value chain. Economic viability depends on the availability of cultivation equipment, harvesting systems, transport infrastructure, storage facilities and a stable end-user for the produced biomass. The analysis by Iliadis et al. (2018) demonstrated that overall costs are highly sensitive to machinery ownership models, transport arrangements and storage systems.

A second success factor is adequate water availability. Cardoon is generally recognised as a drought-tolerant crop capable of producing biomass under Mediterranean rainfall regimes, although higher yields can be achieved under supplementary irrigation (Fernández & Curt, 2006; Gominho et al., 2014).

A third condition concerns efficient biomass storage. Storage directly influences biomass quality, dry matter losses and total supply-chain costs. Iliadis et al. (2018) concluded that protected bulk storage in open windrow piles represented the most economical option for the analysed scenario.

The practice is potentially transferable to other Mediterranean and Southern European post-mining regions where extensive reclaimed land areas coincide with demand for bioenergy. Its main transferable element is not solely the cultivation of cardoon itself but the integrated approach that combines land restoration, perennial biomass production, logistics optimisation and connection to existing energy infrastructure.

Successful transfer would require site-specific validation of soil properties, water availability, expected biomass yield, transport distances, market conditions and energy demand. Transferability is likely to be lower in fragmented landscapes, areas lacking nearby biomass users, or regions where logistics costs would exceed the value of the produced biomass.

The main limitation of this case is that it is primarily a techno-economic assessment rather than a long-term environmental study. Although it demonstrates the feasibility of biomass production on reclaimed mine land, it does not provide evidence on soil carbon sequestration, biodiversity recovery or full greenhouse-gas balances. In addition, the model relies on large, contiguous areas of reclaimed land, which may limit its applicability in smaller or fragmented post-mining sites. Finally, its long-term viability depends on the existence of a stable biomass market and nearby energy users, without which economic sustainability would be difficult to ensure.

Final assessment

The Ptolemaida cardoon case represents a valuable example of energy-oriented post-mining land reuse. Its main contribution lies in demonstrating how reclaimed lignite mine land can be incorporated into a complete biomass supply chain that includes cultivation, harvesting, transport, storage and energy conversion. The approach is particularly relevant for coal-transition regions seeking alternative land uses and new economic opportunities that can build on existing energy infrastructure. Although cardoon is well established as a promising Mediterranean bioenergy crop, the Ptolemaida case focuses primarily on supply-chain organisation and economic feasibility rather than carbon sequestration outcomes. Therefore, the practice should not be described as a verified carbon farming measure. Its climate relevance is mainly associated with renewable energy production, substitution of fossil fuels and potential support for long-term restoration of post-mining landscapes.

Final classification: Good practice for the production of energy biomass in reclaimed post-mining areas, supporting the energy transition and land reuse after lignite mining. The practice shows the potential to generate climate benefits through the development of renewable energy sources and reducing dependence on fossil fuels. At the same time, its impact on long-term carbon storage in the soil requires further research and monitoring.

6.2.5. Czech Republic: Miscanthus Cultivation in in open-pit lignite mine

Description and objectives

As part of the Green Mine project, which focuses on researching innovative approaches to the reclamation of post-mining landscapes. Most using energy crops and second-generation plants, an evaluation of the production parameters of miscanthus is being conducted during the 2025–2026 season in the Most Basin, at the Komořany dump / ČSA open-pit mine. The stands are being re-established using pre-grown plants in biodegradable pots.

Figure 7. An experimental plot with Miscanthus at the Komořany dump / ČSA open-pit mine
Source https://www.ceskenoviny.cz/

Environmental and carbon farming benefits

Miscanthus × giganteus appears to be a suitable crop for the reclamation of dysfunctional and contaminated soils. It is a perennial, highly adaptable plant originating from subtropical regions of Asia (Nsanganwimana et al., 2014; Vávrová et al., 2021). It is capable of efficient water use, and neither its growth nor biomass production are significantly limited during the winter period (Figure 8) (Vávrová et al., 2021). A strong root system combined with organic matter formation contributes to improved soil conditions. Simultaneously, biomass production suitable for energy use is supported, enabling ecological restoration to be combined with economic benefit. Studies suggest that the calorific value of harvested dry biomass is comparable to firewood or brown coal (Nebeská et al., 2019). It supports the recovery of soil microorganisms, improves soil structure, stabilises the soil, protects it against water erosion, and helps immobilise pollutants. It also reaches a maximum height of 3 metres, which limits its effectiveness as protection against wind erosion (Malinská et al., 2020; Al Souki et al., 2021; Nebeská et al., 2018; Nebeská et al., 2021; Pidlisnyuk et al., 2019; Vávrová et al., 2021).

Figure 8. Miscanthus × giganteus.
Source: Vávrová et al. (2021)

Success factors and limitations

Miscanthus × giganteus is notable primarily for its drought resistance, which allows its cultivation and survival even on inhospitable sites. It is also resistant to common pests, reducing care requirements and the need for protective interventions.

Only the hybrid of Giant Miscanthus is suitable for biomass production intended for energy use. It meets requirements both from a production standpoint and in terms of minimising the risk of invasive spread into the landscape. The hybrid spreads by rhizomes only very slowly and is unable to produce viable seeds that could spread into the surrounding environment (Vávrová et al., 2021).

However, it must again be noted that Miscanthus requires several years to reach full vitality and high biomass production. It must also be considered that contaminated or extremely nutrient-poor soils may limit its growth. Initial investment and technological costs may present a further obstacle. The use of Miscanthus therefore requires careful consideration and appropriate management (Malinská et al., 2020; Vávrová et al., 2021). Its disadvantage lies in slower establishment and stand development (2–3 years) and an annual harvest cycle.

Final assessment

Preliminary findings suggest that miscanthus has potential on spoil heap sites; however, specific data on establishment success and plant vitality have not yet been reported, as the results are still expected (greenmine.cz) (Green Mine, 2026).

6.2.6. Czech Republic: Poplars (*Populus* spp.) short-rotation coppice in open-pit lignite mine

Description and objectives

Within the Green Mine project, testing of short-rotation coppice (SRC) species, primarily poplars and willows, is being carried out in the Most **Basin, specifically at the Komořany dump / ČSA open-pit mine, as candidates for biological reclamation of post-mining landscapes. The initial evaluation of the varietal and clonal coppice cultivation trial, in which 2,880 cuttings were planted in May 2025.**

Figure 9. An experimental plot at the Komořany dump / ČSA open-pit mine where a short-rotation coppice have been planted
Source https://vuk.gov.cz

Environmental and carbon farming benefits

The coppicing ability of selected varieties is utilised, enabling repeated harvesting of above-ground biomass in short harvest cycles (2–10 years) without the need to establish new stands throughout their lifespan (15–21 years). Through their cultivation method, coppice plantations in the field create "small copses" or "woodlands" that effectively buffer climatic extremes and fulfil a range of non-productive functions (Vávrová et al., 2021). The poplars show a high tolerance to soil contamination, particularly heavy metals. Thanks to their extensive root system and rapid biomass growth, these trees are widely used in phytoremediation (biological soil remediation).

Success factors and limitations

The overall establishment rate of SRC reached only 38% (ranging from 26% to 64% depending on the variety), which can likely be described as extreme site-driven selection. The most successful varieties were J-105, Monviso, Rokyta, NLB, and Lons x, while Blanc du Poitou and black poplar performed the worst. In terms of site conditions, a dry flat area proved to be the most suitable, outperforming both a moist depression and a dry slope. Regarding planting material, longer cuttings (50 cm) performed better than shorter ones (22 cm). In December 2025, an agrotechnical trial focusing on stem cultivation of SRC was established in parallel, testing four varieties across three sites with two types of planting material, supplemented by a smaller experiment involving the application of biochar and hydrolysate (Green Mine, 2026)

Final assessment

Overall, the results so far indicate that successful establishment of SRC on spoil heaps is possible, but it requires careful selection of suitable varieties and adaptation of planting methods to the specific site conditions.

6.2.7. Czech Republic: Willows (*Salix* spp.) short-rotation coppice

Willow is among the suitable woody plants for reclamation of dysfunctional soils. The study by Kalita et al. (2021) demonstrated that all examined willow species increase soil organic carbon content, which supports improvement in soil quality. Through this ability, willows can significantly contribute to the restoration of soil functions while simultaneously providing biomass suitable for energy use (Kalita et al., 2021). Studies (Vandecasteele et al., 2005; Mleczek et al., 2010) have also demonstrated that numerous willow species and clones can accumulate high concentrations of potentially toxic elements in above-ground biomass. They therefore show considerable potential for use in phytoremediation measures (Vandecasteele et al., 2005; Kuzovkina et Quigley, 2005).

According to Kowalczyk et Kwaśniewski (2021), energy willow plantations can also be used in less fertile areas, where they help stabilise soil and store carbon. The study also found that larger plantations have a lower environmental impact per unit area. This effect is caused by the higher efficiency of technological operations (ploughing, harvesting, transport), which are distributed across a larger area, increasing the overall efficiency of land use for both reclamation and biomass production (Kowalczyk et Kwaśniewski, 2021).

6.2.8. Poland: Meadow communities and common reed cultivation on a hard coal mining waste heap

Description and objectives

The practice was implemented at a waste dump for waste from underground hard coal mining in Libiąż. The site was characterized by very unfavorable habitat conditions, preventing the spontaneous growth of vegetation. The soil was strongly acidic (pH 2.5–4.0), and analyses showed that permissible concentrations of many elements, including chromium, cobalt, and nickel, had been exceeded. The experimental area covered 4,000 m² (50 × 80 m) (Figure 10).

Figure 10. The experimental plot at the Janina Carboniferous rock dump in Libiąż
Source: GIG-PIB

The aim of the project was the biological remediation of a heavily degraded spoil heap by restoring sustainable vegetation cover, reducing erosion, restoring ecosystem functions and producing biomass. An additional objective was to use waste materials to produce a soil substitute capable of neutralising the phytotoxic properties of post-mining waste.

A reclamation substrate mixture was developed consisting of coal mining waste, byproducts of coal combustion, and spent mushroom substrate serving as an organic additive. The mixture was spread over the surface of the spoil heap as a layer of artificial soil substrate, creating conditions conducive to vegetation growth. Subsequently, semi-natural meadow communities and a common reed (Phragmites australis) plantation were established. The sowing of meadow plant seeds and the planting of reed cuttings were carried out by hand.

Environmental and carbon farming benefits

The solution implemented made it possible to effectively restore vegetation to a heavily degraded post-mining area. The meadow communities that developed did not differ in terms of coverage or species composition from those found on native, fertile soils. Common reed achieved a high level of biomass production ranging from 2.48 to 6.24 kg m^{-2} of fresh weight, which corresponds to approximately 12–25 t dry weight ha^{-1}. A sustainable vegetation cover was established, improving surface stability and initiating soil-forming processes.

Despite the very unfavorable properties of the landfill material, the reed biomass was characterized by a low heavy metal content. This indicates limited bioavailability of contaminants due to the use of a reclamation substrate layer. Additionally, the permanent vegetation reduced the risk of waste dusting and the spread of contaminants. A significant reduction in surface temperature was observed compared with non-greened areas.

This practice creates conditions conducive to the accumulation of organic matter thanks to a permanent plant cover, the development of root systems, and high biomass production. Despite the very high initial organic matter (OM) content in the substrate (24.61% in 2020), after 5 years the amount of OM in the soil increased to as much as 27.11%. However, it should be noted that this effect was achieved without regular harvesting and utilization of the above-ground plant biomass.

Consequently, the carbon sequestration effect does not reflect the actual conditions under which energy crops are grown.

Success factors and limitations

A key factor in the success was the use of a specially developed reclamation substrate that neutralizes the phytotoxic properties of mining waste. Equally important was the selection of species tolerant of harsh habitat conditions and the appropriate shaping of the spoil heap’s surface. The authors emphasize that particularly favorable results were achieved on gently sloping terrain, which promotes water retention and reed common growth.

Practical experience demonstrates high potential for application at other post-mining waste dumps where vegetation growth is limited by acidification, phytotoxicity, or a lack of organic matter. However, local validation of the substrate composition and its adaptation to the properties of the waste material present at a given location remain necessary.

The main limitations include:

- limited availability of the component needed to prepare the reclamation substrate (used mushroom substrate);
- high initial carbon content in the reclamation substrate, which under unfavorable conditions may cause the release of carbon dioxide into the atmosphere

- lack of an assessment of the quantity and quality of biomass produced by meadow communities;
- inability to quantitatively assess the carbon farming effect under conditions of full biomass harvest and utilization.

Final assessment

This practice serves as an example of highly effective biological remediation of strongly acidified and phytotoxic post-mining waste. It has been confirmed that waste materials can be used to create a functional soil substitute that supports the development of sustainable plant communities and the production of biomass with low heavy metal content. The lack of above-ground biomass harvest prevents a reliable assessment of the potential for CO2 sequestration.

Final classification: a reclamation practice with high environmental value and high carbon farming potential, requiring further validation of carbon sequestration.

6.2.9. Poland: The steered succession of low Growing Plants on hard coal mining waste heap

Description and objectives

Designed specifically for hard coal waste rock heaps with high potential for future economic redevelopment, the "steered succession of low-growing plants" method is an innovative, cost-effective reclamation technology. Its primary objective is to achieve rapid and affordable greening of degraded surfaces. By stabilizing the soil, this approach mitigates two major risks that can significantly decrease land value and complicate future reuse: the encroachment of invasive species and the spontaneous development of dense woody vegetation. Unlike standard reclamation practices that rely on the expensive importation of topsoil, this technology focuses on accelerating and directing natural succession processes toward a stable, low-growing herbaceous community.

Figure 11. Field study plot of low-growing plants on Północ waste heap (Jankowice – Poland)

Environmental and carbon farming benefits

In terms of their use as an energy source, these communities are olotrophic grasslands and do not produce significant above-ground biomass. Since the experiment has been ongoing since 2025, it is not yet possible to assess its impact on carbon sequestration in the substrat profile (below-ground biomass growth).

However, compared to standard reclamation methods, the communities that have been created are characterized by greater biodiversity with higher aesthetic value. The presence of plant species with showy flowers) (Figure 12), which ensures potential to provide forage for bees (honey production).

Figure 12. The proportion of species with showy flowers that serve as habitats for pollinators.

Success factors and limitations

Experiments conducted at the spoil heap Janina which is owned by PPG and pot experiments using soil provided by the other Project Partners (VUHU, PCC, INNERIS) show that the method used allows for cost-effective revegetation of post-mining areas, both the waste dumps resulting from underground hard coal mining and from open-pit mining. The method creates species-diverse communities that provide habitats for other organisms, particularly pollinators. Covering the area with vegetation limits the spread of invasive species and slows the succession of woody vegetation. For this reason, the method can also be used to ensure the long-term preservation of areas with high potential for economic reuse.

One limitation is the availability of uncontaminated and stabilised sewage sludge, which is the main component of the soil improver. The application of this method may be limited by heavily contaminated and phytotoxic soils where vegetation cannot grow spontaneously.

Final assessment

Although this solution does not create meadow communities characterized by significant biomass growth, it is assumed that vegetation growing directly on barren rock will contribute to long-term carbon accumulation in anthropogenic substrates. In areas where pollution levels are not high, the resulting communities can be used for honey production (agricultural activity). Further research in this area is essential.

6.2.10. Poland: Miscanthus cultivation on contaminated soil

Description and objectives

The plantation of Miscanthus was established in 2015 in Bytom, Poland (50°20′41.9″ N 18°57′19.9″ E). The experimental site was located on farmland contaminated with heavy metals as it was in close proximity to a currently abandoned lead and zinc smelter.

The content of Pb in the soil exceeded the specified limits by 6–7 times for the top layer (0–30 cm) according to the Polish regulation, while the contents of Cd and Zn were 11.5–13 times and 8.5–12 times higher (the soil unsuitable for food production) (Figure 13).

Figure 13. Growing miscanthus on contaminated farmland in Bytom
Source: https://www.miscomar.eu/

The experimental plot was divided into 15 subplots (25 m2). Two rhizomes of Miscanthus giganteus and two novel interspecific seed-based Miscanthus hybrids (GNT41 and GNT34) were planted per m2 in each experimental plot. No fertilizers or inoculum were used during the experiment. The harvest was carried out using hand tools (Figure 14).

Figure 14. Growing miscanthus on contaminated farmland in Bytom
Source: https://www.miscomar.eu/

Environmental and carbon farming benefits

The biomass yield of M × g and the hybrids reached about 16–17 t ha−1 d.m. after the third growing season and 20–24 t ha−1 d.m. after the fourth growing season [Szada-Borzyszkowska et all 2022]. The biogas/methane production, it yields is range from 0,28m3 to ,31 m3 of biogas per kg of organic dry matter [Mangold 2019]. The conducted research confirmed that cultivation of Miscanthus was possible on soils contaminated with heavy metals, without the negative impact of contamination on the quantity and quality of biomass produced, and with a positive effect on the quality of poor soils.The studies showed that Miscanthus tolerates soil Cd levels of 150 mg/kg.

Success factors and limitations

Three-year study shows that cultivation of Miscanthus on soils contaminated with lead, cadmium and zinc is posible. Grass bales (or processed grass pellets) can be burned in specialized biomass boilers to generate heat or electricity or processed into biogas (methane production) [Mangold 2019].. Pellets and briquettes are not recommended for burning in unsuitable individual furnaces. The accumulation of organic matter in the soil within the plantation was not assessed.

Final assessment

Miscanthus have the potential to carbon sequestration and heavy metal soil phytoremediation. While maximising above-ground yield is a significant factor in the carbon savings delivered from perennial biomass cropping, changes in soil carbon stocks must also be accounted for in overall carbon budgets [McCalmont et al., 2018]. To properly measure soil carbon, sampling should be conducted to an appropriate depth (minimum 30 cm) and after a sufficient length of time to detect statistically meaningful stock changes. Additionally, it requires adjusting for changes in bulk density over time, alongside sampling prior to planting or utilizing an appropriate paired site.

6.2.11. Poland: Full-scale experimental phytoremediation plot

Description and objectives

The case concerns a full-scale phytoremediation plot located in the post-industrial and post-mining area of the Upper Silesian Coal Basin, marked in the EDAPHOS project as site CS4. Before the plot was established, environmental characteristics were carried out using remote sensing, drone observations and ecotoxicological studies. The analyses included land cover, vegetation structure and biological status of the area based on RGB imagery, spectral data and field measurements. In 2025, the scope of research was expanded to include multispectral imagery, satellite data and spectral measurements of soil and low vegetation, including the dominant grass species, Veronica chamaedrys and Cirsium vulgare.

Ecotoxicological studies have shown the occurrence of environmental stress while maintaining the biological activity of the soil. Soil toxicity did not exceed 65%, the activity of bacterial dehydrogenases was reduced by about 40%, the inhibition of nematode growth remained below 20%, while their reproduction was reduced by nearly 60%. No significant effect on survival and reproduction of earthworms was found, and soil leachate did not show acute toxicity to Daphnia magna. The results confirmed the suitability of the area for phytoremedial studies.

The aim of the practice is to assess the effectiveness of selected phytoremediation methods in field conditions and to verify their suitability in local soil and climatic conditions. The experiment was designed as a system that combines poplar hybrids with herbaceous plants to support the removal of heavy metals from the substrate.

The plot with an area of about 20 × 50 m was divided into two experimental parts. In the spring of 2025, two poplar hybrids – P10 and PAP153 – were planted, selected on the basis of previous laboratory tests and smaller-scale experiments. For each hybrid, 192 seedlings were planted. Poplar plantings were supplemented with two species of herbaceous plants with the ability to accumulate metals: purple climb (Lablab purpureus) and Sarep mustard (Brassica juncea). These species were grown both in monocultures and in mixed systems with poplars, which made it possible to compare the effectiveness of the different variants. The preparation of the plot included soil preparation, planting, fencing of the area and periodic irrigation using water from a retention tank located in the landfill.

Environmental and carbon farming benefits

The practice allows to evaluate the effectiveness of different plant configurations in the phytoremediation of contaminated sites, with preliminary results indicating higher tolerance to heavy metals and better growth parameters of the PAP153 hybrid compared to P10, especially under medium and high degree of contamination conditions. The environmental safety assessment is based on ecotoxicological studies involving microorganisms, higher plants, soil invertebrates and aquatic organisms exposed to soil leachate. This approach makes it possible to assess the impact of pollutants on different groups of organisms and their potential pathways of movement in the environment. Results on the accumulation of metals in plant biomass are not yet available. The monitoring program assumes annual analyses of poplar leaves and herbaceous plants for the content of arsenic (As), cadmium (Cd), lead (Pb) and zinc (Zn). This will allow to determine the dominant mechanism of the system – phytoextraction, phytostabilisation or a combination of the two – and to develop rules for dealing with the obtained biomass.

The introduction of perennial woody vegetation in post-industrial areas can promote biomass growth, root system development, plant cover maintenance and soil function improvement. However, the potential relevance of the practice for carbon farming remains unconfirmed.

Success factors and limitations

The success of the project was related to the step-by-step selection of plant material preceded by laboratory and semi-technical tests, which made it possible to select the most promising poplar hybrids. Ongoing management of the experiment was also important, including monitoring of plant health, irrigation and protective measures carried out in response to the occurrence of the poplar beetle (Chrysomela populi), periodic droughts and damage caused by game. An important element of the project is also the combination of field observations, ecotoxicological studies and remote sensing monitoring.

The practice can be a model for the full-scale phytoremediation of post-industrial and post-mining areas contaminated with heavy metals. The most important elements that can be transferred include the step-by-step selection of plant material, the use of hybrids of poplar and metal-accumulating plants, and the implementation of environmental monitoring.

However, the possibility of applying the solution in other locations depends on the nature of the pollution, soil properties, water availability, biological pressure and the way biomass is managed. The results obtained for the PAP153 hybrid need to be confirmed under different habitat conditions.

The main limitation is the early stage of project implementation. Currently available results refer to the initial phase of plant development and do not allow for an assessment of the long-term effectiveness of remediation, biomass production, metal accumulation, changes in soil properties or SOC resources.

Additional challenges are pest pressure, periodic water shortages and damage caused by animals. Previous experience indicates that the effectiveness of this type of systems requires constant monitoring and the ability to quickly respond to emerging threats.

Final assessment

The experimental plot is an example of a full-scale application of phytoremediation in post-industrial and post-mining areas. The practice combines the results of previous laboratory tests with field verification, allowing for the comparison of selected poplar hybrids and the evaluation of the effectiveness of mixed systems using metal-accumulating plants.

The results so far indicate better adaptation of the PAP153 hybrid under conditions of heavy metal contamination. Due to the early stage of the project and the lack of data on changes in SOC content, soil function and carbon balance, the practice should be considered as a solution under validation.

Final classification: Good practice of full-scale phytoremediation at the validation stage, relevant for the remediation of contaminated post-industrial and post-mining sites; a practice of potential importance for carbon farming.

6.2.12. Germany: Energy crop field trial on a former sewage sludge deposit site

Description and objectives

The case concerns a field experiment with energy crops established on the site of a former sewage sludge landfill in Leipzig (Saxony, Germany). The area was characterized by heavy metal pollution, which limited the possibility of conventional agricultural use. Although the site is not a post-mining site, it is a valuable example of degraded land management, allowing the assessment of the possibility of combining biomass production with phytoremediation functions.

The study included Miscanthus × giganteus, Sida hermaphrodita, Spartina pectinata and Panicum virgatum. These species were selected for their high biomass productivity, perennial nature of crops, and potential ability to stabilise or absorb pollutants. The practice answers one of the key questions regarding the development of degraded areas – whether it is possible to produce useful biomass while maintaining environmental safety and limiting the transfer of metals to the above-ground parts of plants.

The aim of the study was to assess the possibility of growing perennial energy crops on land contaminated with heavy metals and to determine their potential for simultaneous biomass production and support for phytoremediation processes. An additional objective was to determine the impact of agrotechnical activities on plant functioning under environmental stress.

The study covered the effects of cultivation carried out without additional treatments with variants including NPK fertilization and the use of the Emfarma Plus® microbial inoculum (Pogrzeba et al., 2018).

The experiment was established in 2014 on soil contaminated with heavy metals. Four species of energy plants were grown in three variants: without additional treatments, with NPK fertilization and with the use of the Emfarma Plus® microbiological preparation. The experiment made it possible to assess the impact of both the characteristics of individual species and the applied supporting activities on plant growth and pollutant uptake. This allowed us to analyse the effectiveness of different biomass production strategies on degraded sites.

Environmental and carbon farming benefits

The research confirmed the possibility of using selected perennial energy crops in polluted areas as an alternative to traditional agricultural use. It was particularly important to demonstrate that most of the analysed species produced above-ground biomass with a relatively low content of heavy metals. The most favorable results were obtained for *Miscanthus × giganteus*, *Sida hermaphrodita* and *Spartina pectinata*. A different reaction was observed in the case of Panicum virgatum, which accumulated higher amounts of zinc despite the limited bioavailability of this element in the soil.

These results indicate that the safety of biomass use depends not only on the degree of soil contamination, but also on the biological properties of the cultivated species (Pogrzeba et al., 2018).

The most important environmental aspect of the analysed practice is the reduction of the transfer of heavy metals to biomass intended for further use. The results obtained indicate that appropriate selection of species may enable the production of biomass in polluted areas while maintaining a relatively low concentration of metals in the above-ground parts of plants. At the same time, the case of Panicum virgatum shows that safety assessment cannot be based solely on soil analysis. It is necessary to monitor the quality of biomass and verify the content of pollutants before its energy use.

Perennial energy crops can help maintain permanent plant cover, develop root systems, reduce erosion, and improve soil function. However, data on soil organic carbon (SOC), soil organic matter (SOM), volumetric density, underground biomass, soil respiration or carbon balance are not presented. Therefore, the practice should be considered as an example of biomass production and management of contaminated areas with potential importance for carbon farming, but without the possibility of confirming the effects associated with carbon sequestration.

Success factors and limitations

The key condition for success was the proper selection of species adapted to the conditions of the contaminated substrate. The results of the experiment show that individual plants react differently to the presence of heavy metals, which requires an individual assessment of their suitability. Quality control of the obtained biomass is also important. Even with proper plant growth, biomass may not meet the requirements related to its subsequent energy use. Therefore, monitoring the content of pollutants should be an integral element of this type of undertaking. In addition, the results indicate the importance of supportive measures, such as fertilization and the use of microbiological preparations, which can affect plant growth and the preservation of pollutants in the soil environment.

The practice can be used as a model for assessing the suitability of energy crops in degraded and polluted areas. Its most important element is the combination of testing of different species with biomass quality analysis and assessment of heavy metal uptake.

However, the transfer of the solution to other areas requires local validation, as the properties of post-mining areas, metal-contaminated soils and former sewage sludge landfills can vary significantly in terms of soil pH, organic matter content, pollutant mobility or water availability. For this reason, practice should be treated primarily as a model of conduct.

The most important limitation is the lack of detailed data on yield size, which makes it difficult to assess the production efficiency of individual species. Another limitation is the lack of data on changes in soil properties and organic carbon resources. In addition, the available information does not include an assessment of the quality of products produced during the energy use of biomass, including ash, combustion residues or by-products of biological biomass processing processes.

Final assessment

The experiment in Leipzig is a valuable example of the controlled cultivation of perennial energy crops in areas contaminated with heavy metals. Its most important contribution is to demonstrate that the safety of such a solution depends primarily on the proper selection of species and monitoring of biomass quality, and not only on the level of soil pollution. The results indicate that *Miscanthus × giganteus*, Sida hermaphrodita and Spartina pectinata showed more favourable properties in terms of biomass quality than Panicum virgatum, which was characterized by higher zinc accumulation.

The practice should be interpreted as an example of productive use of contaminated land aimed at biomass production and supporting phytoremediation processes. Due to the lack of data on changes in SOC stocks and carbon balance, it cannot currently be considered a verified practice of carbon farming.

Final classification: Good practice for biomass production and phytoremediation in contaminated sites, providing valuable information on the safety of biomass obtained from land contaminated with heavy metals; a practice of potential importance for carbon farming.

6.2.13. Sweden: Energy Willow Case Study

Swedish energy willow cultivation is a strong positive example of combining biomass production with measurable water and soil benefits. The case is best supported by evidence on commercial deployment, groundwater protection, soil carbon gains, and policy-enabled adoption (Dimitriou et al., 2012).

Description And Objectives

In Sweden, short-rotation coppice willow has been grown on agricultural land since the late 1980s to produce biomass for energy, with the harvested material used in district heating and combined heat-and-power systems. The system was not designed only for fuel supply; it was also developed to use nutrient-rich residual streams such as wastewater, landfill leachate, sewage sludge, wood ash, and industrial wastewaters in a productive way. The core objective was therefore dual: to produce renewable biomass while reducing pollutant and excess nutrient loads in soils and waters through plant uptake and associated microbial processes. This dual-use model reached meaningful commercial scale, with 891 farmers planting willow across 56 municipalities between 1986 and 1996 (Dimitriou et al., 2005; Dimitriou et al.,2012; Mola-Yudego et al., 2008).

Environmental Benefits

The strongest documented environmental benefit is lower nitrogen leakage than under conventional arable cropping. Across 16 Swedish locations monitored over three growing seasons, nitrate leaching to groundwater was significantly lower under willow SRC than under adjacent cereal fields. In a separate 9-year field study on sandy soil in southwest Sweden, groundwater nitrate-N and ammonium-N were generally below 0.5 mg/L, and intensive willow management was judged not to be a major threat to groundwater quality. The carbon-farming case is also strong. In 14 long-term Swedish SRC fields, soil organic carbon was significantly higher than in adjacent conventionally managed arable soils, averaging 9% higher in topsoil and 27% higher in subsoil. The same comparison found 12% lower cadmium in SRC topsoil, while chromium, copper, nickel, lead, and zinc did not differ significantly, which suggests carbon gains did not come with broad trace-element accumulation (Dimitriou et al., 2012; Aronsson et al., 2000).

Success Factors And Limitations

A key success factor was the fit between willow supply and Sweden's district heating expansion. Adoption rose sharply when subsidies, fossil-fuel taxes, and increased wood-fuel capacity in district heating systems acted together, with the model estimating almost a 70% increase in farmers planting willow during the study period. Another success factor was economic and agronomic integration: nutrient-rich residuals functioned both as treatment targets and as low-cost fertilizers that could raise biomass production while lowering waste-treatment costs. The limitations are important and should be stated explicitly. Although nitrate losses were lower, phosphate concentrations in groundwater under SRC were higher than under reference cereal fields, and this increase was not explained by sewage sludge application. The groundwater results were also cautious rather than absolute: nitrogen concentrations occasionally exceeded 5 mg/L in the first and third years in the long-term field study, even though the overall impact remained moderate (Aronsson et al., 2000; Mola-Yudego et al., 2008; Dimitriou et al., 2005).

Final Assessment

As a case study, Swedish willow SRC is a credible positive example of multifunctional land use: it supplied bioenergy feedstock at commercial scale, reduced nitrate leaching relative to cereals, increased soil organic carbon, and enabled productive use of residual nutrient streams. Its success depended on policy support and district-heating demand, and its environmental balance is favorable but not uniform because phosphorus losses remained a real trade-off.

Overall, Sweden’s energy willow system is a strong positive example of carbon farming and ecological intensification, especially where biomass markets, waste-resource recycling, and water-protection goals are aligned.

6.2.14. Comparative synthesis of lessons learned

LESSON 1

Most of the available reclamation practices create conditions conducive to carbon accumulation, but their impact on SOC resources is still poorly documented.

The analyzed cases show that contemporary mining site reclamation projects increasingly combine environmental and production goals with activities that can potentially support carbon sequestration. Restoring vegetation cover, introducing perennial woody vegetation, reducing erosion and increasing the supply of organic matter to the soil create conditions conducive to the growth of soil carbon resources.

At the same time, the analysis of the case studies indicates that most of the projects were designed primarily for reclamation, land stabilisation, restoration of ecosystem functions or future economic development of the site, rather than for the quantitative assessment of carbon sequestration. As a consequence, monitoring soil organic carbon content (SOC), volume density, carbon balance or changes in carbon resources is not the main objective of the research and is not demonstrated.

This result in itself is an important observation. It shows that there is already a wide base of reclamation practices potentially supporting carbon farming, while the next step should be to include indicators related to the accumulation and durability of carbon in the soil in their monitoring. For this reason, most of the analyzed cases should be treated as reclamation practices of potential importance for carbon farming, which can be the basis for further development and assessment of climate effects.

LESSON 2

Post-mining areas can perform diverse environmental and economic functions beyond basic biological reclamation.

The analysed case studies show that properly carried out reclamation activities can create new production and ecosystem functions, for example the good practice "*Robinia pseudoacacia for mine land reclamation and development of apiculture*" combines erosion protection with the development of a useful base for beekeeping and honey production, and the "*Experimental fruit orchards on rehabilitated old mine soils in the West Macedonia Lignite Centre*" confirms the possibility of conducting selected fruit crops on reclaimed post-mining land, with the effects depending on the species and variety. An alternative direction of development is presented by the practice "*Aromatic plant cultivation on reclaimed lignite mine land*", which includes the cultivation of oregano, lavender, rosemary and sage in areas after lignite mining. These examples show that reclamation can support not only the restoration of vegetation, but also the development of economic activities, soil protection, support for pollinators and diversification of land uses.

At the same time, the experience from the analysed locations indicates that the effectiveness of individual solutions remains strongly related to habitat conditions, substrate properties, water availability and the selection of plant species.

LESSON 3

The effectiveness of reclamation is due to a comprehensive approach that includes substrate preparation, selection of plant material and long-term management.

A comparison of the analyzed cases indicates that the success of reclamation activities depends on many interacting elements, and not only on the use of a specific plant species. The example of the reclamation of the mining waste heap in Libiąż based on the succession of low vegetation shows the importance of appropriate preparation of the substrate using mixtures of mining waste, coal combustion products and organic materials, while in the case of the "Full-scale experimental phytoremediation plot", the step-by-step selection of poplar hybrids preceded by laboratory and semi-technical tests and ongoing management of the experiment including protection against the pests, irrigation and monitoring of plant development. Similar relationships were observed in the case of experimental orchards and aromatic crops, where the effectiveness of cultivation was related both to the properties of the substrate and to the appropriate selection of species and methods of plantation.

The analysed experience indicates that the most valuable element of good practices is a comprehensive process including the diagnosis of the condition of the site, the preparation of the site, the selection of plant material, the implementation of activities and the monitoring of their effects.

LESSON 4

Environmental safety is a fundamental element of the assessment of the production use of post-mining areas

All the analysed practices indicate the importance of environmental monitoring as a condition for responsible management of degraded areas. In the case of 'Experimental fruit orchards on rehabilitated old mine soils in the West Macedonia Lignite Centre', the fruit production capability was assessed not only through the prism of yield, but also on the basis of heavy metal content tests in the fruit. In turn, the Polish practice "Full-scale experimental phytoremediation plot" includes a multi-level ecotoxicological assessment and planned monitoring of arsenic, cadmium, lead and zinc content in plant tissues. Also in the case of biomass and phytoremediation crops, the issue of safety concerns not only the condition of the soil, but also the further management of biomass that can accumulate pollutants.

These experiences show that the assessment of the effectiveness of reclamation should take into account both production aspects and environmental safety and the quality of the products obtained.

LESSON 5

The transferability of practices is based on the adaptation of proven solutions to local environmental conditions.

The practice "Experimental fruit orchards on rehabilitated old mine soils in the West Macedonia Lignite Centre" shows the importance of appropriate soil conditions, drainage and product safety monitoring. Similarly, "Aromatic plant cultivation on reclaimed lignite mine land" can be a model for the non-food use of post-mining land, but its effectiveness depends on the properties of the substrate, climatic conditions and the final use of the raw material. Also, the experiments from "Robinia pseudoacacia for mine land reclamation and development of apiculture", "Full-scale experimental phytoremediation plot" and examples using miscanthus, confirm that this is a species with a wide ecological amplitude, capable of growing in various conditions, including difficult ones. When using black locust to establish fast-growing tree plantations or for and honey production, it is important to remember that it is an invasive species characterized by a strong ability to colonize new areas and is difficult to eliminate.

In practice, the most universal element of knowledge transfer is the use of a proven scheme of conduct including diagnosis of the baseline, selection of appropriate methods, risk assessment and long-term monitoring of effects. This approach increases the possibility of effective implementation of solutions supporting restoration, the development of ecosystem services and potential climate benefits.

LESSON 6

Practices with limited effectiveness or in the validation phase provide important information on the conditions for the application of good practices.

The analyzed cases show that not all reclamation activities lead to unambiguously positive results. Both partial successes and solutions that are still in the testing phase provide valuable information about the conditions, limitations and risks associated with the implementation of individual practices. This is particularly important in post-mining areas, where the effects of reclamation depend on the co-occurrence of many factors, such as the properties of the substrate, the level of pollution, water conditions, the local microclimate, biological pressure, and the way in which plantings are conducted and maintained.

A good example is experimental fruit orchards on rehabilitated old mine soils in Greece, which confirmed the possibility of conducting selected fruit crops on reclaimed post-mining land, at the same time indicating a large diversity of reactions of individual species and varieties. The best results were obtained for vines, cherries, walnuts, apple trees and hazelnuts, while peaches and persimmons were susceptible to frost damage, raspberries showed poor adaptation to soil conditions, and pears and quinces were strongly limited by fire blight. This case shows that agricultural reclamation requires the selection of specific species and varieties adapted to local habitat conditions.

Similar conclusions can be drawn from the experience of short-rotation plantations (SRC) carried out in post-mining areas in the Czech Republic. Although SRC systems have the potential to produce biomass and stabilise land, the effectiveness of plantation establishment was highly dependent on local habitat conditions and the planting material used. The results highlight the importance of prior verification of varieties, selection of planting technology and adaptation of practice to site specifics.

The example of willow cultivation in Sweden shows that one of the key factors in the successful implementation of energy crop cultivation is ensuring the efficient utilisation of the biomass produced.

The system for producing and collecting biomass must not require it to be transported over long distances.

Practices currently in the validation phase offer a different kind of experience. “Aromatic plant cultivation on reclaimed lignite mine land in Greece” confirms the possibility of using reclaimed land for the production of non-standard agricultural crops; however, the available data do not yet include information on crop yields, product quality, contaminant uptake, or changes in soil properties. Similarly, the “Full-scale experimental phytoremediation plot” in Poland is an advanced example of field phytoremediation, but assessing its effectiveness requires further data on biomass production, metal accumulation, changes in soil properties, and long-term environmental effects.

LESSON 7

Reclamation of post-mining areas can also support ecosystem services and agricultural activities beyond direct biomass production

Post-mining areas can also be used indirectly for agricultural production by planting nectar-producing plants and producing honey. In this case, there is no need to create fertile habitat; rather, the key factors are the selection of the target plant species composition and the possibility of using a low-cost growth-promoting additive for pioneer vegetation. Controlled succession of low-growing vegetation on post-mining sites effectively supports land greening, biodiversity, and the creation of habitats for pollinators; however, its significance for biomass production or carbon sequestration remains difficult to assess at this time. In contrast, the reclaimed technogenic substrates with meadow vegetation and common reed in Libiąż confirm the high effectiveness of restoring the biological functions of degraded areas; however, interpreting the effects related to carbon sequestration is difficult due to the high initial organic matter content in the substrate used, and the lack of regular harvesting of above-ground biomass.

The most important conclusion is that cases which are at the testing stage or show limited effectiveness do not constitute a weakness of the set of practices under analysis. On the contrary, they help to identify the conditions for success, the scope of applicability and the areas requiring further research and monitoring. Taking such experiences into account enhances the credibility of the recommendations and enables a more realistic assessment of the potential for post-mining land restoration. This is particularly significant in the context of carbon farming, where the premature transfer of solutions without taking local conditions into account could lead to an overestimation of climate benefits or the inappropriate selection of land-use practices.

6.3. SIENIAWA - an example of mining operations with full-scale agricultural use of post-mining land

From the very beginning, the SIENIAWA Brown Coal Mine Sp. z o. o. has adopted the principle that reclamation is conducted concurrently with mining operations, not only after they have ceased. This approach reduces the area of land temporarily closed for use and allows for a faster return of the areas to economic use. Reclamation at the SIENIAWA Brown Coal Mine is conducted in the direction of agricultural and forestry use.

In the first stage of mining, overburden masses are used to fill previously mined-out excavations. After switching to internal dumping, the terrain is reconstructed by successively backfilling the excavations. This is followed by topsoiling, i.e., the spreading of a layer of humus soil, and agrotechnical measures aimed at restoring the soil's biological activity.

One element of best practice is to conduct reclamation in parallel with mining operations. This limits the scale of landscape transformation and allows for the areas to be returned to use more quickly. Additionally, overburden from new excavations is used to fill previously exploited open pits, which reduces the need to create external dumping grounds.

Once the surface formation is complete, the following steps are performed:

- reconstruction of the terrain by backfilling the excavations (Figure 15),
- spreading the humus layer (humus application) (Figure 16),
- agrotechnical treatments that restore soil biological activity (Figure 17),
- preparing land for agricultural use (Figure 18).

Figure 15. ***SIENIAWA - reconstruction of the terrain by backfilling the excavations.***

Figure 16. ***SIENIAWA - spreading the humus layer (humus application).***

Figure 17. ***SIENIAWA - agrotechnical treatments that restore soil biological activity.***

Figure 18. ***SIENIAWA - preparing land for agricultural use.***

After completing basic technical procedures, biological reclamation begins. At this stage, melilot is typically sown at the SIENIAWA Mine, preparing the soil for further agricultural use (Figure 19).

Figure 19***. SIENIAWA - Meliot sown as part of biological reclamation.***

Melilot is valued because:

- it fixes nitrogen from the air thanks to the nodule bacteria living on its roots, enriching the soil,
- it develops a deep root system (up to 1 meter deep) that loosens the soil,
- it provides a large amount of organic matter after ploughing,
- it reduces erosion and stabilizes the surface of spoil heaps,
- it prepares the soil for subsequent agricultural crops.

At a later stage, once the land has been properly prepared, peas are grown (Figure 20).

Figure 201. ***SIENIAWA – Peas growing at the reclaimed post-mining area.***

SIENIAWA's approach is a good practice because it restores productive agriculture quickly and safely by sequencing engineering and biology. The mine rebuilds landforms first by backfilling and shaping pits to gentle, field-friendly slopes, isolates any acid-forming materials beneath a protective cap, and reapplies a substantial humus/topsoil layer so crops have a stable, uniform rooting zone. Soil chemistry and structure are then reactivated with targeted liming and agrotechnical treatments, followed immediately by a legume cover (melilot) that fixes nitrogen, deepens and loosens the soil, adds organic matter, and shields the fresh surface from erosion. Only after this foundation is in place does the site transition to food crops like peas, demonstrating real, near-term productivity while maintaining long-term flexibility for rotations, including energy crops. The result is faster return to use, reduced environmental risk, visible benefits for local stakeholders, and alignment with carbon-farming principles through continuous living cover and rising soil organic carbon.

6.3.1. Factors influencing suitability of the SIENIAWA

This chapter defines the factors that will influence suitability of the SIENIAWA post-mining area for cultivating energy crops as part of, or as a temporary phase within, agricultural reclamation. It integrates site conditions and ongoing reclamation practices to later identify feasible species-site matches, mitigation measures, and a monitoring set that supports carbon farming co-benefits and renewable biomass production (COFA Deliverable 5.2).

Geological and soil setting

The SIENIAWA lignite deposits are embedded in a glaciotectonically disturbed sequence. During the last glaciation, the bedrock was folded and displaced, creating local basins and elevated ridges that still shape today's topography and influenced where open-pit mining could proceed. The overburden is dominated by disturbed Neogene silts, accompanied by Quaternary sands and gravels and local clays and tills. Agronomically, these materials are typically low in nitrogen and in plant-available phosphorus and potassium, so reclaimed soils start out nutrient-poor unless amended.

During mining and reclamation, carbonaceous and sulfur-bearing layers that occur near the lignite seam are carefully isolated from the surface. Standard practice at SIENIAWA is to place such acid-prone materials deep in the profile and cap them with more benign sands or clays. This prevents acidification of the root zone and protects young crops. At the same time, the biologically active topsoil (humus) is conserved from the excavation edges and reapplied during landform restoration. In most areas the working target is a roughly 40 cm humus/topsoil cap over the shaped surface. Naturally developed soil thickness across the landscape is highly variable - ranging from bare sandy rises with almost no topsoil to depressions where fine sediments accumulate and the soil layer can exceed 50 cm - so the applied cap helps standardize rooting conditions for crops.

Hydrology and terrain

Groundwater conditions are favorable for surface reclamation. The first regional aquifer generally lies 10-40 m below ground, so shallow rooting crops rarely interact with it. However, the same clay and silt lenses that record the area's glacial history can perch water locally above them, creating seasonally wet patches. Small kettle-type depressions also retain surface water after rain. These moisture contrasts matter for crop placement: drought-tolerant perennials are better suited to the elevated, freely draining caps, while short-rotation coppice or wet-tolerant grasses can occupy the wetter margins and depressions.

Newly formed surfaces made from silts and sands are initially vulnerable to erosion by wind and water. To manage this, SIENIAWA shapes reclaimed agricultural land with gentle, stable slopes and reserves steeper shaping for forestry buffers. In engineering shorthand, the project uses target "slope ratios":

- 1:7 for agricultural areas means a 1 unit rise for every 7 units of horizontal run. That's a gentle slope of maximum 14%. Such geometry reduces runoff speed and makes it easier for crops to establish without the surface washing or blowing away.
- 1:3 for forestry interfaces means a 1 unit rise for every 3 units of run - about a 33% slope. These steeper faces are kept under trees or shrubs whose roots bind the soil, while agricultural rows are kept back from the edge.

Reclamation practice at SIENIAWA

Reclamation is conducted in parallel with mining rather than waiting until extraction ends. Overburden from new cuts is used to backfill earlier pits (internal dumping), and the landform is restored to blend with the surrounding topography. As soon as the surface is shaped, the conserved topsoil is spread as a cap, and agrotechnical measures begin to restart soil biological activity.

Where there is any risk of acidity from sulfur-bearing materials, lime is applied to neutralize acidity and bring soil pH into a range suitable for plant growth. At SIENIAWA, long-standing experience shows that rates on the order of 20 tonnes of agricultural lime per hectare are effective where needed; actual doses are adjusted to measured pH and buffering capacity. Because the base materials (silts, sands, clays) are low in plant-available phosphorus and potassium, those nutrients are supplied according to soil tests, with nitrogen kept moderate during early establishment.

Biological reclamation starts early. Legume covers - such as melilotus - are sown to protect the surface, fix atmospheric nitrogen through root nodules, and add organic matter. Melilotus also develops a deep rooting system (often exceeding 1 m) that improves soil structure and porosity. This cover phase reduces erosion risk, builds soil function, and prepares the site for the next stage, whether that is energy crop establishment or a transition to conventional agriculture. Continuous cover, gentle slope geometry, and isolation of acid-forming layers together create the stable platform required for introducing perennial energy crops in suitable microsites.

The site-specific scenario for agricultural reclamation at SIENIAWA mining and post-mining areas will be proposed as part of COFA Deliverable 5.2 (Report on Agricultural Reclamation Scenarios).

6.4. Recommended agricultural practices

Practices recommended for biomass production, reclamation and carbon farming potential

The analysed case studies demonstrate that post-mining and degraded lands can support a broad spectrum of productive, environmental and restoration functions. Depending on local conditions, these areas may be used for biomass production, ecological restoration, specialised agricultural production and other forms of productive land reuse. At the same time, the review confirms that the suitability of a given practice should be evaluated not only in terms of plant establishment or biomass yield and its uses, but also with regard to environmental safety, long-term site functionality and supporting the provision of ecosystem services including climate-change mitigation.

The strongest evidence currently supports perennial vegetation systems, including energy crops, short-rotation coppice, phytoremediation plantations and non-food crops. Compared with conventional food production, these systems are generally better adapted to the limitations of post-mining environments, as they provide continuous soil cover, support substrate stabilisation, reduce erosion risks and facilitate the gradual restoration of ecological functions. In several cases, they also create opportunities for productive land use while limiting the direct transfer of contaminants into the food chain.

The reviewed practices further indicate that many reclamation measures may contribute indirectly to carbon farming objectives through the establishment of perennial vegetation, increased biomass production and long-term soil protection. However, the available evidence also shows that carbon-related effects are rarely monitored systematically within reclamation projects. As a result, most practices should currently be regarded as reclamation and biomass-production systems with potential relevance for carbon farming rather than fully verified carbon farming practices.

Consequently, the practices presented in table below are recommended as conditional good practices. Their successful implementation depends on site-specific assessment, appropriate species or cultivar selection, environmental safety monitoring and, where climate benefits are claimed, the inclusion of long-term soil organic carbon (SOC) monitoring.

Table 4. Recommended agricultural practices for biomass production, reclamation and carbon farming potential.

Recommended practice	Conditions for use	Key advantages	Main limitations
Perennial energy crops (*Miscanthus* × *giganteus*, *Sida hermaphrodita*, *Spartina pectinata* and selected grasses)	Degraded, contaminated or marginal land unsuitable for food production; prior soil assessment required	Biomass production combined with soil protection and potential phytoremediation; documented performance on heavy-metal-contaminated soils	Biomass quality must be controlled; metal uptake differs among species; insufficient SOC data for carbon farming verification
Cardoon (*Cynara cardunculus*) cultivation for biomass supply chains	Large post-mining areas located near heat or energy facilities	Proven biomass production potential and established logistics model for energy use	Limited information on SOC dynamics, soil improvement and long-term carbon effects; dependent on local energy infrastructure

Recommended practice	Conditions for use	Key advantages	Main limitations
Short-rotation coppice (SRC) with willow and poplar varieties	Sites with locally validated clones and appropriate management conditions	Repeated biomass harvests, soil stabilisation, bioenergy production and phytoremediation potential	Strong site dependence; variable establishment success; biomass quality requires monitoring where contamination occurs
Creation of a fertile layer of reclamation soil using waste materials with meadow vegetation or common reed plantation	Highly acidic and phytotoxic hard-coal waste heaps	Enables vegetation establishment on severely degraded substrates; supports biomass production and ecological restoration	Requires availability of suitable substrate components; carbon sequestration effects remain insufficiently quantified
Steered succession of low-growing plant communities	Areas prioritising erosion control, biodiversity enhancement and low-cost revegetation	Low-cost ecological restoration; supports pollinators and limits invasive species succession	Limited biomass production; carbon benefits remain largely unquantified
Full-scale remediation system	Contaminated post-industrial and post-mining land under controlled monitoring conditions	Integrates remediation, ecotoxicological assessment and long-term environmental monitoring	Long-term results on metal removal, soil improvement and SOC are not yet available
Aromatic plant cultivation on reclaimed mine land	Reclaimed sites suitable for non-food production and product-quality monitoring	Diversifies productive land use and creates opportunities for high-value crops	Limited evidence regarding yield, product quality, contaminant uptake and soil improvement
Selective fruit orchards on rehabilitated mine soils	Pilot-scale agricultural rehabilitation with soil testing and food-safety monitoring	Demonstrates the feasibility of selected fruit crops on reclaimed soils	Strong dependence on species, cultivar and site conditions; not currently supported by carbon-monitoring data

Recommended use of the practices

From the perspective of post-mining land management, perennial and non-food systems offer the broadest opportunities for combining ecological restoration with productive land use. Practices based on Miscanthus, willow and poplar SRC plantations, cardoon cultivation, aromatic crops and phytoremediation systems appear particularly suitable where soil contamination, substrate limitations or environmental constraints reduce the feasibility of conventional food production.

Fruit orchards and aromatic plants represent promising options for agricultural reuse of reclaimed land where appropriate soil conditions and product safety can be demonstrated. However, these approaches should be implemented gradually and accompanied by monitoring programmes addressing both agronomic performance and the quality of harvested products.

A more cautious approach is required when assessing carbon farming potential. The establishment of perennial vegetation, long-term soil cover and increased biomass production may create favourable conditions for soil carbon accumulation, but reliable quantification requires documented baseline conditions and systematic monitoring of SOC stocks and related soil parameters over time. Until such evidence is available, the climate benefits of most reviewed practices should be considered plausible but not yet fully quantified.

7. Integrating food and energy crops at a landscape scale

A strict separation of food crops on productive land and energy crops on marginal land is not the strongest biodiversity strategy in European agricultural landscapes; the literature more often supports selective integration of perennial bioenergy crops into diversified, landscape-scale farming systems. The evidence is not unconditional: benefits depend on crop type, spatial arrangement, management intensity, existing habitat value, and scale of deployment, so the core question is not integration versus segregation in the abstract, but where, what, and how much to integrate (Dauber et al., 2016; Winberg et al., 2023; Calvin et al., 2021).

7.1. Conceptual basis

The integration-versus-segregation debate in bioenergy maps directly onto the broader land sharing versus land sparing framework for biodiversity conservation. In this framing, segregation restricts energy crops to marginal, degraded, abandoned, or newly spared land, while integration combines food and energy crops within rotations, fields, farms, or structural landscape elements such as hedgerows and agroforestry strips (Dauber et al., 2016).

In Europe, the strongest conceptual argument against strict segregation is that biodiversity decline is driven mainly by intensive productive farmland, so moving energy crops away from those landscapes does little to repair the simplified crop mosaics and habitat deficits that caused the problem (Dauber et al., 2016; Reckling et al., 2023; Triquet et al., 2024). Reviews of sustainable intensification and EU agri-biodiversity policy likewise conclude that effective solutions require holistic land allocation, coordinated regional action, and landscape-scale design rather than isolated farm decisions (Weltin et al., 2018; Falcao et al., 2021).

Integrated systems can take several forms, including energy crops embedded in crop rotations, perennial strips or hedgerows, and mixed farm mosaics that combine food production with dedicated biomass patches. Experimental evidence from Europe and Brazil shows that such integration can maintain food yields while increasing total biomass output: sunn hemp rotations kept wheat near regional average yields and raised cumulative biomass 1.5- to 2-fold, while also avoiding detectable declines in soil fertility indicators (Dauber et al., 2016; Zegzada-Lizarazu et al., 2022).

7.2. Evidence across strategies

The table below presents landscape-scale strategies for integrating food and energy crops, along with their main advantages and limitations.

Table 5. Landscape-scale strategies for combining food and energy crops, with their main benefits and constraints.

Strategy	Main Rationale	Typical Benefit	Main Limitation
Strict segregation on marginal land	Reduce direct competition with food crops	Can avoid using prime cropland (Perez et al., 2022).	Does not remove water competition and can shift pressure onto biodiverse semi-natural land (Perez et al., 2022; Hodgson et al., 2024).
Integration on arable land	Increase heterogeneity within working farmland	Often yields synergies for biodiversity and ecosystem services, especially with perennial 2G crops (Winberg et al., 2023).	Poor design can still create local trade-offs (Dauber et al., 2016).
Large-scale monoculture expansion	Maximize feedstock supply efficiency	Can contribute to mitigation goals (Calvin et al., 2021).	Risks biodiversity loss, monocultures, and landscape segregation (Winberg et al., 2023; Dauber et al., 2016).
Spatially targeted perennial integration	Place biomass where ecosystem services gains are highest	Can reduce erosion, nutrient loss, flooding risk, and improve carbon storage and biodiversity (Englund et al., 2020).	Needs spatial planning, policy support, and compensation for public benefits (Englund et al., 2020; Rega et al., 2020).

7.3. Biodiversity and Ecosystem Services

The biodiversity case for integration rests largely on heterogeneity. A global meta-analysis across 6,397 fields found consistently positive effects of both crop and landscape heterogeneity on plants, invertebrates, vertebrates, pollinators, and predators across temperate and tropical systems, including annual and perennial cropping systems (Priyadarshana et al., 2024). This supports the idea that adding perennial energy crops in small, spatially dispersed units is more likely to help biodiversity than concentrating them into large blocks (Winberg et al., 2023; Dauber et al., 2010).

Recent temperate European evidence also weakens the assumption that productivity and biodiversity are inherently opposed. In 49 Swiss 1-km² landscapes using real yield data from 299 farmers, food production and biodiversity were not predominantly antagonistic, especially where semi-natural habitats made up at least 20% of the landscape; negative bird-production relationships emerged mainly in landscapes dominated by farmland at roughly 64-74% cover. That result strengthens the argument that the surrounding landscape context, not only the crop category, determines whether integration succeeds (Zingg et al., 2024).

Perennial bioenergy crops appear especially promising because they can generate ecosystem-service co-benefits beyond biomass. Reviews report that strategically integrating perennials into intensive agricultural landscapes can improve biodiversity, reduce soil erosion and nutrient losses, increase soil carbon, enhance pollination, and mitigate flooding. Miscanthus in particular has been valued at €1,200-4,183 per hectare per year in environmental services, with stronger benefits on marginal agricultural land, and its integration into European systems appears to aid both landscape diversification and socio-economic welfare (Englund et al., 2020; Von Cossel et al., 2020).

The evidence is less favorable for assuming that marginal land automatically solves the food-versus-fuel problem. Reviews of temperate bioenergy systems conclude that cultivating biomass on marginal or abandoned land cannot fully resolve biodiversity and ecosystem-service trade-offs, partly because the ecological value of such land is under-studied and sometimes high (Winberg et al., 2023). Scenario studies do show that carefully delineated fringe or marginal areas can support positive habitat connectivity and biodiversity outcomes, but only when natural and semi-natural classes are explicitly preserved during planning (Cervelli et al., 2020).

7.4. Policy and Implementation

The practical challenge is that benefits from integrated systems are public and spatial, while costs are private and farm-specific. Wider adoption of multifunctional perennial systems is limited by weak markets and inadequate policy compensation for ecosystem services, even when environmental gains are well documented (Englund et al., 2020; Von Cossel et al., 2020). Recent policy analysis therefore argues that perennial biomass crops can contribute to CAP objectives only if they are carefully integrated into farming systems and landscapes, supported by incentives, verification systems, and long-term research and market development (Clifton-Brown et al., 2023).

Spatial targeting is central to implementation. European land-classification work now provides crop-management intensity maps that can support more context-specific territorial policy, while landscape-policy reviews argue that collective farmer action and ecologically grounded spatial planning are necessary because most biodiversity processes operate above the field scale Falco et al., 2021; Rega et al., 2020). This matters because the same bioenergy crop can produce different outcomes depending on whether it is inserted as a few small fields, as a rotational break, or as large feedstock blocks linked to centralized processing (Winberg et al., 2023; Dauber et al., 2010).

Several newer reviews converge on a qualified integration strategy. Miscanthus expansion in the UK is no longer framed only as a marginal-land option; it is also considered suitable as a rotational break on arable land with yield decline or weed pressure and as a diversification option on improved grasslands, provided it complements rather than displaces food production (Hodgson et al., 2024). More broadly, climate-mitigation reviews conclude that widespread monocultures can meet carbon goals but create other sustainability harms, whereas strategic integration into existing agricultural landscapes may deliver fewer absolute mitigation gains but better overall sustainability outcomes (Calvin et al., 2021).

A final implementation constraint is the evidence base itself. Most European biodiversity evidence still comes from field-scale studies of conventional practices such as fertilization, tillage, mowing, and grazing, while diversification measures such as intercropping, agroforestry, and intermediate cropping remain under-studied in field settings (Triquet et al., 2024). That gap supports caution: integration appears more promising than segregation in Europe, but its success still depends on locally informed design, farmer participation, and protection of existing semi-natural habitats and high-carbon land (Weltin et al., 2018; Kernecker et al., 2026; Calvin et al., 2021).

In sum, the literature supports integrating food and energy crops at the landscape scale more than strictly segregating them, especially when perennial biomass crops are spatially targeted to diversify intensive farmland rather than replace valuable semi-natural land. The strongest chapter conclusion is therefore conditional but clear: in Europe, integration is usually the better default strategy, while segregation remains useful only in carefully screened areas where it avoids both food displacement and ecological damage.

8. Summary and Conclusions

This report demonstrates that post-mining areas can become valuable resources for sustainable land management, climate change mitigation, renewable energy production. Despite a wide range of risks and limiting factors, the cultivation of energy crops and carbon farming in post-mining areas is possible. Key to overcoming technical challenges is both the proper implementation of technical reclamation and the appropriate selection of crop species and cultivation methods. The selection of a crop variety should be based on a comprehensive risk analysis, and it is essential to evaluate its performance under test conditions (experimental plots in post-mining areas).

Overall, the analysed case studies indicate that successful post-mining land management relies on integrated approaches that combine ecological restoration, productive reuse and long-term environmental monitoring. The review of carbon farming practices confirms that post-mining lands have substantial potential to contribute to climate mitigation through the restoration of vegetation cover, enhancement of soil organic carbon stocks, and long-term biomass production. However, the report also demonstrates that biomass production alone does not constitute evidence of carbon sequestration. Reliable carbon farming requires baseline assessments, systematic monitoring of soil organic carbon, clearly defined carbon accounting methodologies, and compliance with emerging European regulatory frameworks. As a result, many existing reclamation projects should currently be classified as practices with carbon farming potential rather than fully verified carbon farming systems.

However, it should be emphasised that structured process consisting of site diagnosis, adaptation of interventions to local conditions, environmental risk management and continuous evaluation of outcomes is essential. Such an approach provides the strongest basis for achieving both reclamation objectives and potential long-term climate benefits.

The evaluation of energy crop cultivation shows that perennial species such as Miscanthus, willow, poplar, cardoon, common reed, and other dedicated biomass crops are particularly well suited to reclaimed post-mining environments. These species combine relatively low cultivation requirements with high biomass production, soil stabilization capacity, and resilience to environmental stresses. The use of crop varieties that require annual cultivation of the topsoil (e.g., plowing) may be significantly hindered or impossible due to unfavorable soil properties (high stone content, heavy and compacted subsoil). Given the size of the cultivated area, the fact that mechanisation of the cultivation process is not possible practically rules out the rationality of establishing energy crop plantations. It is advantageous if cultivation on post-mining land can be carried out using standard agricultural machinery.

For biomass production, priority should be given to systems supported by clearly defined utilisation pathways, including established logistics chains, storage capacity and end-users. In the target scenario for the development of post-mining areas for energy crop cultivation, it is essential to include not only on crop performance but also on market access, transport distances and the availability of energy conversion infrastructure.

Species identified as capable of growing on degraded land, can be used for direct combustion in commercial power stations or domestic stoves (mainly woody species), for biogas production (mainly grassy species), and for biodiesel production (e.g. camelina sativa).

When developing agriculture scenarios for the use of heavily degraded post-mining land, consideration should be given to the possibility of using energy crops or pioneer species to improve habitat conditions (e.g. by enriching the soil with organic matter and using phytoremediation to treat contamination). Once the land has been cleaned up and made fertile, target crops that are more demanding – including those used for food production – can then be introduced.

9. References

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Annex 1

Table 6. Properties of plants grown for energy purposes

Plants grown for energy purposes[1]		Technical factors			Soil requirements				Meteorological factors	Resistance to spring frosts	Resistance to temperature fluctuations (high/ medium/ low)	Resistance heat waves and drought resistance	Resistance to changes in groundwater levels	Resistance to soil erosion	Resistance to soil compession	Resistance to soil salinization	Resistance to soil contamination	Resistance to pests	yield Calorific value	Suitable for the reclamation of post-industrial sites
		Yield	How the crop is used	Cultivation method	Optimal soil pH	Organic / mineral soils	Nutritional requirements	Granulometric composition of the substrate heavy, light, skeletal soils	Annual precipitation											YES/NO
Trees and shrubs	**Energy willow *(Salix energiae)***	Above-ground biomas yield: 3,9 – 4,8 Mg/ha/year m² of dry in poor soil conditions and 19,6 Mg/ha/year on fertile soils matter [Mizak 2009]	After drying and chipping, biomass is used for combustion in residential furnaces and commercial power generation. Willow woody SRC biomass are appropriate for other thermochemical conversion processes, such as torrefaction, carbonization, gasification, pyrolysis, liquefaction, or combustion (Štochlová et all 2019)	Cultivation and harvesting using specialized agricultural equipment (willow planters and forager)—a fully mechanized process	pH 5.5-8.0 [Kuzovkina et al. 2018]	The energy willow (Salix) can be successfully grown in both mineral and organic soils. While it produces the highest yields on fertile, moist mineral soils (such as loams), its high tolerance allows it to thrive on organic peat-muck soils and marginal [Stoolarski 2019]	The annual nutrient requirement for willow cultivation is 130kg/ha fo nitrogen 34 kg/ha for phosphorus 155kg/ha for potassium	Energy willow (Salix viminalis) thrives best in medium to heavy soils, particularly clay loams, as they provide superior moisture retention and aeration. While it can tolerate lighter sandy soils, they often struggle with drought, reducing overall biomass yields unless heavily irrigated [2]	"annual rainfall of 900-1,100mm are best" [Teagasc 2025]	yes (cold tolerant) [Lafleur et al. 2017]	high [Lafleur et al. 2017]	medium-high [Palm et al.. 2022]	Optimal groundwater level 1-1.5 m [Świtajska et al.. 2014], resistant to periodic flooding [Mizak 2009]	high [Wilts et al.. 2024]	medium [Kuzovkina et al. 2018]	tolerates salinity [Palm et al.. 2022]	high [Renninger et al..2024]	medium [Sulima et al.. 2017] Rust (melampsora) is the major disease of willow. A severe attack can reduce yields by 40% and in some cases kill plants [2]	LHV = 8.374 HJ/Mg [Stolarski et al.. 2025]; Higher Heating Value (HHV)= 10-14 MJ/kg dry weight [Janas & Zawadzka 2017]	YES [Smart & Cameron 2008]

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Plants grown for energy purposes[1]	Technical factors			Soil requirements				Meteorological factors	Resistance to spring frosts	Resistance to temperature fluctuations (high/ medium/ low)	Resistance heat waves and drought resistance	Resistance to changes in groundwater levels	Resistance to soil erosion	Resistance to soil compession	Resistance to soil salinization	Resistance to soil contamination	Resistance to pests	yield Calorific value	Suitable for the reclamation of post-industrial sites
	Yield	How the crop is used	Cultivation method	Optimal soil pH	Organic / mineral soils	Nutritional requirements	Granulometric composition of the substrate heavy, light, skeletal soils	Annual precipitation											YES/NO
Native poplar *(Populus alba, P. nigra)*	Above-ground biomas yield: From 8 to 12 t ha⁻¹ y r⁻¹ of dry biomass [NIemczyk 2016]	Shor rotation poplar wood is not suitable for construction purposes. After chipping, biomass is used in commercial power generation. After drying can be used in residential furnacess . The most effective rotation cycle is between 3 and 5 years.	On flat fields, planting and harvesting are mechanized using specialized machinery (poplar planters and harvesters). On sloped terrain, planting is done by hand and harvesting is done using chainsaws	(Populus nigra) prefers a neutral to mildly alkaline soil. P.,) is generally more adaptable, thriving in highly alkaline conditions but capable of tolerating acidic soils as well. Both trees generally grow best in the pH 6.0 to 8.0 (Caudullo 2016)	P nigra requires organic soil, while P alba can tolerate soil with a lower organic matter conten	P, alba has lower nutritional requirement s. It thrives in poorer sandy and gravelly soils. P nigra It requires very fertile soil, rich in nutrients	P. alba prefers lighter soil, P nigra prefers heavy soils	"Over the area of its natural distribution, average annual rainfall ranges from less than 380 mm to over 1400 mm" [Wilkinson]	no data	P. nigra) and P. alba) are highly resistant to frost and daily temperature fluctuations. The white poplar (Populus alba) tolerates heat and intense sunlight better than the black poplar (Populus nigra).	P. alba tolerates occasional droughts well, P. nigra absolutely requires high humidity	P. alba tolerates occasional flooding, dies on soils that are permanently waterlogged , while P. nigra absolutely requires high a high groundwater level it copes well with temporary flooding	high	Both white poplar (Populus alba) and black poplar (Populus nigra) do not tolerate heavy soil compaction well.	Both the white poplar (Populus alba) and the black poplar (Populus nigra) show moderate tolerance to soil salinity. The white poplar performs better in saline soils	Both white poplar (Populus alba) and black poplar (Populus nigra) show a high tolerance to soil contamination, particularly heavy metals. Thanks to their extensive root system and rapid biomass growth, these trees are widely used in phytoremediation (biological soil remediation).	Low - both species are susceptible to many pests and diseases {EFSA 2025]		YES
Hybrid poplar *(Populus hybrida)*	Above-ground biomas yield: from 8 to 16 t ha⁻¹ y r⁻¹ of dry biomass [Niemczyk 2016]	Shor rotation poplar wood is not suitable for construction purposes. After chipping, biomass is used in commercial power generation. After drying can be used in residential furnaces. The most effective rotation cycle for energy purposes is between 3 and 5 years.	On flat fields, planting and harvesting are mechanized using specialized machinery (poplar planters and harvesters). On sloped terrain, planting is done by hand and harvesting is done using chainsaws. Most of the hybrid poplar cultivars gave higher biomass productivity over an initial 6-year cycle (Niemczyk 2016)	pH 6.0-7.0 [Demeritt Jr. 1990]	mineral soils [Demeritt Jr. 1990]	Requiring substantial nutrient and water inputs to achieve their rapid biomass potential. Their success depends on a steady supply of Nitrogen (N), Phosphorus (P), and Potassium (K), combined with strict soil conditions and weed control [Young 2000]	Hybrids grow well on upland and bottom-land soils if the soils have good moisture-holding capacities and are of medium texture." [Demeritt Jr. 1990]	Hybrid poplars require roughly 600 mm to 850 mm of annual precipitation or water availability to sustain optimal growth rates [Fontenla-Razzetto el al.. 2022; Chhin 2010]	Medium [Schreiber et al.. 2012]	Medium - temperature fluctuations can have important effects on growth, though there were few effects on leaf gas exchange [Cerasoli et al..2014]	Low - but research allowing for increased thermal tolerance [Guo et al..2010; Merino et.al 2014; Jia et al..2017]	Medium to high [Schume et al.. 2004]	"The planting of hybrid poplars did not decrease soil losses compared to the control plot, regardless of the tree planting density." [Remaury et al.. 2019]	"Best performance was found on strongly-compacted, poorly-drained clay soils" [Clark A.W. 1995]	"Significant improvement in salt tolerance of poplar hybrids with different salt 2 tolerant varieties." [Changjun et al.. 2024]	"The hybrids between section Aigeiros and Tacamahaca (QHQ and QHB) and the inter-specific hybrid 107 within section Aigeiros were more resistant to composite heavy metal stress than the other poplar varieties were partially because of their high levels of free proline that exceeded 93 μg·g−1 FW." [Li et al. 2024]	Medium - several biotic stresses, such as attacks by pests and pathogens, severely affect poplar production and productivity." [Sharan et al.. 2024]	HHV = 17.69 - 20.75 MJ/kg [Carmona et al.. 2015]	YES [Madejon et al.. 2025]

	Plants grown for energy purposes[1]		Technical factors		Soil requirements				Meteorological factors											Suitable for the reclamation of post-industrial sites
		Yield	How the crop is used	Cultivation method	Optimal soil pH	Organic / mineral soils	Nutritional requirements	Granulometric composition of the substrate heavy, light, skeletal soils	Annual precipitation	Resistance to spring frosts	Resistance to temperature fluctuations (high/ medium/ low)	Resistance heat waves and drought resistance	Resistance to changes in groundwater levels	Resistance to soil erosion	Resistance to soil compession	Resistance to soil salinization	Resistance to soil contamination	Resistance to pests	yield Calorific value	YES/NO
	Black Locust *(Robinia pseudoacacia L.)*	Above-ground dry biomass yield: 8.3 – 20.1 Mg DM/ha/year in SRC under Central European conditions (2–5 year rotation). Nitrogen-fixing species, so performs well on poor soils. [Alesso et al. 2021; Böhm et al. 2011]	Wood suitable for agriculture and industrial use. [Rédei et al. 2017]	Planting by rhizome cuttings or seedlings (spring). SRC management: 2–5 year rotation. Mechanized harvesting. Coppices vigorously after cutting. [Rédei et al. 2017]		Can grow in sandy soil with a low content of total organic carbon, a low sorption capaci-ty and deficient nutrient supply. [Böhm et al. 2011]	Capable of colonising very low nutrient substrates due to symbiosis with nitrogen fixing bacteria, Rhizobium sp. [Rédei et al. 2014]	Demands well aerated, light soils, but tolerates a wide range of edaphic conditions. Fine sands and light loamy soil types are good for black locust, provided the depth of the soil is enough. [Böhm et al. 2011; Rédei et al. 2017]	Capable of surviving between ~500–550 mm/year without irrigation. [Rédei et al. 2014]	high – frost hardy to −30°C [Rédei et al. 2014]	high [Rédei et al. 2014]	very high – one of the most drought-tolerant energy tree crops; deep taproot system; documented survival under severe Mediterranean summer drought [Dini-Papanastasi 2008]		Characterized by an extensive root system and thus widely used for land protection and soil erosion control. [Zhou & Shangguan 2005]			used in reclamation of coal mine spoils in Germany and Central Europe. [Böhm et al. 2011]			YES - Deemed to be a suitable tree species for soil regeneration and reclaiming former mine sites. [Böhm et al. 2011]
Grasses	**Miscanthus giganteus *(Miscanthus giganteus)***	Above-ground biomas yield12.06.2026 14.5 t/ha [Bilsndzija et al. 2021]	After chipping, biomass is used for combustion in commercial power generation [co-firing with coal]. Grass bales (or processed grass pellets) can be burned in specialized biomass boilers to generate heat or electricity or processed into biogas (methane production). Pellets and briquettes are not recommended for burning in unsuitable individual furnaces.	Mechanized planting using planters. Harvesting using a corn combine with a forage chopper. Establishment: Requires careful weed control during the first two growing seasons because Miscanthus is a poor competitor in its early establishment phase.	pH 5.5-7.5 [Malinska et al.. 2020]	Miscanthus is able to grow on a wide range of soils, from humus-rich sandy substrates to deeper loamy soils rich in soil organic matter, and is undemanding in terms of nutrient supply. Vranová, 2015	It has exceptionally low fertilizer requirements because it is a highly efficient perennial grass. The crop only demands small amounts of Nitrogen (N), Phosphorus (P), and Potassium (K) to sustain its growth.	thrives best in deep, fertile loamy or sandy loam soils with high water-retention capacity. However, it is an incredibly hardy crop that adapts to most soil types—including clay, peat, and light sandy soils—as long as the ground is well-draining and not waterlogged	"It is best suited to locations receiving at least 30 inches per year of annual rainfall" (762 mm) [United States Department of Agriculture 2011]	yes (cold tolerant) [White et al. [ed]. 2021])	high [White et al. [ed]. 2021]) Distinctive by its resistance to cold temperatures when maintaining a suffi cient photosynthesis rate	high (drought tolerant) [da Costa et al.. 2018]	tolerates wetlands [Newton et al.. 2025] . Research shows it produces significantly greater height and biomass in saturated wetland environments compared to upland habitats [Turnage 2022]	high [Nelson et al.. 2025]	low-medium [Newton et al.. 2025]	"tolerate moderate soil salinity" [Sater et al.. 2025]	high [Souki et al.. 2021]. Plant root exudates contain numerous enzymes necessary for organic matter decomposition Rejšek et al., 2012	medium [Burdova et al.. 2023]	Lower Heating Value LHV =16.7 MJ/kg [Lisowski et al.. 2018]; HHV = 18-19 MJ/kg [Newton et al. 2024] . For biogas/methane production, it yields 0,28m3 -0,31 m3 of biogas per kg of organic dry matter [Mangold 2019]	YES [Jeżowski et al.. 2017]

Plants grown for energy purposes[1]		Technical factors			Soil requirements				Meteorological factors	Resistance to spring frosts	Resistance to temperature fluctuations (high/ medium/ low)	Resistance heat waves and drought resistance	Resistance to changes in groundwater levels	Resistance to soil erosion	Resistance to soil compession	Resistance to soil salinization	Resistance to soil contamination	Resistance to pests	yield Calorific value	Suitable for the reclamation of post-industrial sites
		Yield	How the crop is used	Cultivation method	Optimal soil pH	Organic / mineral soils	Nutritional requirements	Granulometric composition of the substrate heavy, light, skeletal soils	Annual precipitation											YES/NO
	Meadow vegetation (native species)	Above-ground biomas yield: Under optimal production conditions, as 10,2 Mg ha−1 of dry biomass per year	After chipping, biomass is used for combustion in commercial power generation [co-firing with coal]. Grass bales (or processed grass pellets) can be burned in specialized biomass boilers to generate heat or electricity or processed into biogas (methane production). Pellets and briquettes are not recommended for burning in unsuitable individual furnaces.	Mechanized sowing, cutting and baling: The process relies on conventional agricultural machinery.	A wide range of soil parameters. It is essential to select the appropriate plant species composition.	A wide range of soil parameters. It is essential to select the appropriate plant species composition.	A wide range of soil parameters. It is essential to select the appropriate plant species composition. For energy efficiency reasons, nitrogen fertilization is kept to the absolute minimum (typically around {60–90 kg N/ha, as excess nitrogen degrades the quality of biomass intended for combustion (increasing emissions of harmful substances and the slag content of the ash).	A wide range of soil parameters. It is essential to select the appropriate plant species composition.	The optimal amount of rainfall for hay meadows ranges from 500 to 700 mm per year,	With the right choice of species- high	With the right choice of species- high	With the right choice of species- high	With the right choice of species- high	With the right choice of species- high	With the right choice of species- high	With the right choice of species- high	With the right choice of species- high	high		YES [Vítěz, 2015]

		Technical factors		Soil requirements				Meteorological factors											Suitable for the reclamation of post-industrial sites
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Phragmites australis	Czech Republic (on wetlands): 5 070g/m2 [Vymazyl & Kropfelova 2005]; Europe: aboveground peak biomass of 10–30 t dry matter ha−1 y−1 [Geurts et al.. 2020]. The yield provided by common reed cultivation ranged from , 2.48–6.24 kg/m2 fresh biomass. This typically corresponds to about 12–25 metric tons per hectare of dry biomass per hectare. The biomass was characterized by a low heavy metal content [Więckol-Ryk et al. 2025].	"Commonreed biomass has acknowledged utility and market value as a raw material for bioenergy (biogas and biofuels), construction materials and paper pulp and as an ecological tool for water purification and wetland conservation. " [Więckol-Ryk et al. 2025]	Mechanized planting using planters. Harvesting using a corn combine with a forage chopper On wetlands specialized combine harvesters.An improvement in soil cover through fertilization and management practices, such as mowing, appears appropriate to enhance biomass yield [Kulik et al.]	"Numerous studies confirmed that Phragmites australis grows in soils with different pH, salinity, fertility and texture levels. Therefore, this species can grow in different climatic conditions" [Więckol-Ryk et al. 2025 based on Karunaratne & Asaeda 2023] "According to Hazelton and Murphy, the optimal pH for various plants ranges between 5 and 8" [Więckol-Ryk et al. 2025 based on Hazelton & Murphy 2016]	Organic and mineral soils [Geurts et al.. 2020]	"The higher concentration of nitrogen influences the higher biomass of Phragmites australis. The phosphorus concentration is irrelevant to the test plant growth." [Więckol-Ryk et al. 2025 based on Tao & Hui 2012]	"Common reed vegetation was observed on substrates with the highest fine particle size fraction, which was associated with a slow water flow or temporary water stagnation, where the tiniest particles settled in the hollows." [Więckol-Ryk et al. 2025]	Annual rainfall of 900-1,100mm are optimal, Although precipitation is important, its growth is determined to a much greater extent by the groundwater level and soil moisture [Zhang, et al 2022].	no ("Phragmites australis is very sensitive to extreme weather events (e.g. frost and flooding) and less sensitive to less rapid changes (e.g. seasonal change to winter at 3600 m in Nepal and prolonged periods of drought in Australia), " [Packer et al.. 2017])	high (based on [Eller et al.. 2017])	high ("P. australis can withstand water stress or drought for a relatively long period of time." [Pagten et al.. 2005])	high - It prefers moist, periodically flooded soils—it can tolerate temporary drought	"reduces wind erosion" [Więckol-Ryk et al. 2025]; "Phragmites sequesters nutrients, heavy metals and carbon, builds and stabilizes soils, and creates self-maintaining vegetation in urban and industrial areas where many plants do not thrive." [Kiviat 2013]	no data	high	high	high	NCV: 16.58 MJ/kg (dry basis) / 15.33 MJ/kg (as received) [Alexiou Ivanova wt al.. 2024]	YES
Switchgrass (Panicum virgatum)	Switchgrass yield is typically moderate to high but varies strongly with ecotype, site, stand age, and management. Across U.S. field datasets, mean biomass yield was 8.7 Mg/ha for upland and 12.9 Mg/ha for lowland ecotypes, while field-scale marginal-land trials averaged 6.3 Mg/ha . (Wullschleger et al., 2010;	Switchgrass is used mainly as a lignocellulosic bioenergy crop, especially for cellulosic ethanol and other biofuels, because its biomass can be converted into ethanol, biogas, pyrolysis products, and biobased chemicals. It also retains important non-energy uses: it was originally adopted as a forage crop, is still used for hay and grazing, and	Switchgrass is usually established from seed in spring, using adapted cultivars, shallow planting, and strong first-year weed control. No-till drilling often improves establishment and stand density. (Parrish et al., 2009; Kumar et al., 2021)	The evidence supports a mid-range optimum rather than an extreme acidic or alkaline optimum: germination was optimal at pH 6.0, good from 6 to 8, and field establishment was recommended at pH 5 to 8. Greenhouse optimization for biomass similarly	Switchgrass grows on mineral soils ranging from sandy wasteland to loam and clay, and it is often used on marginal agricultural land rather than high-organic soils (Slessarev et al., 2020).	Switchgrass is a low-input crop, but yield usually improves when N is supplied, especially on nutrient-poor sites. Nutrient limitation is often more important for establishment and sustained biomass than for simple survival. (Chakrabort	Good yields are possible on sandy-loam and sandy wasteland, though site quality remains limiting (Nasso et al.., 2015)	Higher precipitation can substantially increase growth: in one experiment, +50% and +33% rainfall increased aboveground biomass by 56.5% and 49.6%, while severe drought reduced biomass by 38.9%. (Hui et al., 2018)	Spring frosts: resistance is medium to high in upland genotypes, which cold-acclimate 5–7°C earlier and show much lower winterkill than lowland types. Temperature fluctuations: resistance is medium overall; upland genotypes handle rapid fall cooling better, but combined heat plus drought causes extra stress. Heat waves and drought: resistance is high to medium; switchgrass is adapted to hot, dry climates, but multi-year drought and combined heat-drought reduce biomass. (Willick et al., 2022; Hayford et al., 2022; Ayyappan et al., 2024).			Soil erosion: resistance is high because replacing row crops with switchgrass cut soil loss by 43.7%–95.5% and reduced runoff by 3.2%–12.1% . Soil compaction: direct tolerance evidence is limited, but 7-year establishment decreased bulk density and increased soil porosity, suggesting switchgrass can ameliorate compacted soils. Soil salinization: resistance is medium to high; yields were unchanged under treated wastewater despite rising salinity and sodicity, and gypsum or sulfur reduced sodicity. Soil contamination: resistance is medium, with tolerance to Cd and moderate Ni, but severe Ni reduced yields 55%–60% and Cr caused total plant loss. (Wang et al., 2020; Zhao et al., 2022; Chaganti et al., 2021; Gomes et al., 2022)					resistance is genotype-dependent	heating value is consistently about 18.4–18.7 MJ/kg (Gomes et al.., 2022)	YES Switchgrass is repeatedly described as a viable reclamation species on reclaimed surface mines and other degraded industrial lands.

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		Fike et al., 2017)	can provide wildlife habitat, giving producers flexibility between biomass and livestock markets. (Larnaudie et al., 2022; Wang et al., 2020)		placed the productive pH window at 6.33 to 8.12, depending on water availability . (Hanson et al., 2005; Zhang et al., 2015)		y et al., 2025)													
Perennials	**Virginia mallow *(Malva virginiana)***	biomass yields are low in the establishment years and generally exceed 10 Mg DM ha⁻¹ after the first 2 years, with reported values roughly 8.7–20.3 Mg DM ha⁻¹ in established stands. Root cuttings (vegetative propagation) often produced the highest yields. Nahm & Morhart 2018) DM content 50–90% depending on harvest time. (Vanja et al, 2025)	use for combustion, pellets, briquettes, biogas/biomethane, steam gasification, phytoremediation, and fibre extraction/industrial applications within a circular bioeconomy. Pellet densities exceeding 650 kg/m³, and specifically states Sida pellets reached at least 1094 kg/m³. (Nahm & Morhart 2018)	It is a perennial crop that regrows from rhizomes/rootstock and has a reported lifespan of 15–20 years. Biomass productivity depends on the establishment method, with root cuttings often producing the highest yields. The crop can be harvested using conventional harvesting machinery. (Nahm & Morhart 2018; Vanja et al. 2025).	performs best on slightly acidic to neutral soils and that soil pH is an important factor affecting growth. (Nahm & Morhart 2018)	Grows on mineral soils; tolerates moderately degraded soils (Nahm & Morhart 2018)	responds positively to nitrogen fertilisation, and several studies found increased biomass yield with N application. (Nahm & Morhart 2018)		biomass production is reduced by water limitation and drought despite some drought resistance. (Nahm & Morhart 2018)	high – perennial root system survives hard frosts; hardy to −20°C [Nahm & Morhart 2018]	high	medium – moderately drought-tolerant; performance declines significantly under severe summer drought. Less drought-tolerant than Miscanthus or Jerusalem artichoke. [Nahm & Morhart 2018]		high – perennial deep root system reduces soil erosion			high – documented phytoremediation of heavy metals (Cd, Zn, Pb); suitable for contaminated post-industrial soils. [Nahm & Morhart 2018]	few serious pest and disease problems compared with many crops and mentions several pathogens/insects [Nahm & Morhart 2018]	Net calorific value (dry mass): 17.5–18.4 MJ kg⁻¹ DM, depending on harvest time and plant fraction [Nahm & Morhart 2018]	YES (conditional) – documented on post-industrial soils with phytoremediation purpose; performance at Ptolemais needs field verification due to dry summer conditions. Suitable as a soil-improvement pioneer species if irrigation is available. [Nahm & Morhart 2018]

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Annual	**Biomass sorghum (annual, transitional)**	Reported yields vary by type and environment e.g. biomass sorghum reached 22.2–37.5 Mg/ha dry biomass in one fertilization study and 57.97 Mg/ha dry biomass at first harvest in semi-arid conditions. (Bartzilis et al., 2020; Nascimento et al., 2026). Sweet sorghum reached 40.6 t/ha in Southern Ukraine at 350 mm annual precipitation (Bazaluk et al., 2021).	Sorghum combines food, feed, and bioenergy use with broad adaptation to semi-arid, hot, and low-input environments. (Ameen, 2024).	Studies most often describe row or furrow planting with defined spacing and thinning, plus mineral fertilization and active weed control. (Hailermiam et al., 2023).	The supported pH range is broad: 5.2–8.5 is considered adequate, while field soils near 6.9–8.0 supported cultivation in organic and conventional systems. (Nanganoa et al., 2020; Chinmai et al., 2024)	Performs on low-fertility mineral soils, but organic inputs improve fertility and yield. (Chinmai et al., 2024).	N, P, and K as main limiting nutrients (Srivastava et al., 2025)	Sandy soils are a severe limitation because of low fertility (Issine et al., 2022).	Sorghum is consistently described as a warm-season crop adapted to hot, dry climates. Resistance to heat waves and drought is high relative to many cereals, supported by C4 photosynthesis, deep roots, thick wax, stay-green traits, and osmotic adjustment. That tolerance is not absolute: drought, especially post-flowering, still reduces grain yield, biomass, and quality. Temperature fluctuations: resistance appears medium to high, because sorghum tolerates high temperatures but remains sensitive when climate extremes exceed its limits. Groundwater or flooding change: tolerance is medium; sorghum can tolerate flooding or submergence better than many cereals, but waterlogging reduces root oxygen and yield potential. (Khalifa et al., 2023; Srivastava et al., 2025; Borrell et al., 2024; Issiné et al., 2022; Abreha et al., 2021; Behera et al., 2022).					Soil erosion: likely moderate to high control once established, but the supplied papers do not directly quantify erosion reduction.	Soil compaction: direct evidence is limited, though organic management reduced bulk density by 16% in sorghum fields (Chinmai et al. 2024)	Sorghum generally tolerates moderate salinity, not severe salinity, and multiple studies describe it as suitable for saline or saline-alkaline marginal soils. Salt tolerance varies strongly by genotype, with broad screening studies repeatedly identifying tolerant and sensitive lines across grain and sweet sorghum (Mansour et al., 2021; Huang et al., 2018; Amombo et al., 2022)	Sorghum can grow on metal-contaminated soils and is repeatedly described as a high-biomass, metal-tolerant candidate for phytoremediation (Perlein et al., 2021; Ofori-Agyemang et al., 2024). The strongest field evidence shows that sweet sorghum hybrids had no obvious toxicity symptoms across Zn-, Pb-, and Cd-contaminated sites (Yuan et al., 2019).	Pests: pests and pathogens reduce yield and quality, but resistance is genotype- and management-dependent rather than uniformly high (Srivastava et al., 2025).	Calorific evidence is consistent that sorghum biomass is energetically useful, though value depends on product form. Raw sorghum distillery residue had a calorific value of 17.15 MJ/kg, increasing to 22.36–23.37 MJ/kg after wet torrefaction (Chen et al., 2021)	YES The literature supports a yes, especially for bioenergy-oriented reclamation rather than food use. Multiple studies place sorghum on reclaimed, marginal, contaminated, or otherwise unproductive land while still reporting workable biomass and energy outputs. (Zuo et al., 2019; Nenciu et al., 2021; Roman et al., 2025)

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	Yield	How the crop is used	Cultivation method	Optimal soil pH	Organic / mineral soils	Nutritional requirements	Granulometric composition of the substrate heavy, light, skeletal soils	Annual precipitation											YES/NO
False flax/Gold-of-pleasure (Camelina sativa)	Seed yield: 10–20 dt/ha = 1.0–2.0 Mg/ha for winter camelina: 20–25 dt/ha = 2.0–2.5 Mg/ha [Kurasiak-Popowska 2024] The seed yield in Germany is about 1.9 t/ha, France—2.8 t/ha, Poland—1.75 t/ha, USA—2.3 t/ha, Lithuania—from 0. 8 to 2.1 t/ha. The seed yields can reach up to 1.1 t/ha even under conditions of limiting nutrients or water. Under favorable conditions, camelina crops yield more than 3 t/ha" [Juodka et al. 2022]	Seeds used to produce oil that can be processed for biodiesel purposes. The oil has health benefits and can be used for culinary purposes - high content of unsaturated fatty oils [Karčauskienė 2014]	Standard methods, as with cereal crops, involving plowing, sowing, and harvesting with a combine harvester.	"The ideal soil pH range for camelina is 5.6 to 6.5, although camelina can tolerate pH values as low as 5.0." [Moore et al. 2019] It tolerate moderate soil acidity well and yield the highest harvests in soils rich in calcium [Walter et al. 2025] .	It can be grown under different climatic and soil conditions, but not in organic or clay soils [Zubr 2003]	It quickly absorbs water and nutrients from the soil and has little need for mineral and organic fertilizers [Zubr 2003]	perform best in moderately compact soils, whereas yields are generally lower in waterlogged, clayey, and loamy soils [Walter et al. 2025]	"Seasonal water requirements range from 332–490 mm for C. sativa based upon cumulative evapotranspiration (ET) estimates" [Neupane et al. 2022]	yes [Waraich et al.. 2013]	high tolerance to temperature fluctuations towards cold, but no data on heat tolerance [Waraich et al.. 2013]	yes [Waraich et al.. 2013]	yes ("the least sensitive to temporary water shortages in the soil of all cruciferous plants" [Kurasiak-Popowska 2024]	"reduce soil erosion" [Neupane et al.. 2022]	no data	high ("salinity only has a temporary effect on camelina seed germination") [Zanetti & Mastroberardino 2025]	yes [Park et al. 2014]	yes [Neupane et al. 2022]	Seed: 14.13 MJ/kg, 17.88 MJ/kg; Cake: 9:11 MJ/kg [Juodka et al.. 2022]	YES [Park et al. 2014]