



Guidelines for Soil Regeneration and Reclamation Practices

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EXECUTIVE SUMMARY

Post-mining land degradation remains a major environmental and socio-economic hurdle for European coal regions currently undergoing transition. Mining activities often result in altered landforms and the creation of substrates characterized by poor fertility, acidity, or contamination. These regions require a shift beyond simple land stabilization toward long-term soil regeneration to support productive and sustainable land uses. This process involves a range of activities from technical reclamation, which focuses on engineering stability, to biological reclamation, which aims to restore the living soil functions necessary for agriculture.

Agricultural reclamation is a primary direction for the COFA Project, but it is a demanding pathway that must be tailored to the intended use of the biomass. The report identifies several distinct pathways, with food-crop reclamation representing the most sensitive category. This direction requires strict evidence that contaminant bioavailability and crop uptake are low enough to protect the human food chain. Fodder and grazing reclamation similarly necessitate careful management, as pollutants can transfer from the soil to forage and eventually into livestock products like milk and meat. For sites that are marginal or moderately contaminated, industrial and energy-crop reclamation offer suitable alternatives. These systems reduce direct food-chain exposure while still providing necessary vegetation cover, soil stabilization, and economic value.

The success of agricultural strategies depends on a site-specific diagnosis of soil dysfunctions, which serves as the foundation for selecting appropriate reclamation practices. Physical dysfunctions, such as erosion and deep compaction, often require selective soil handling and targeted mechanical loosening combined with rapid revegetation to restore rooting depth and surface stability. Hydrological rehabilitation focuses on restoring the soil's ability to infiltrate and retain water, which is essential for crop resilience against both drought and waterlogging. Chemical corrections, including pH adjustment through liming or managing salinity through drainage, are required to create a stable environment for plant growth. When contamination is present, the focus shifts toward remediation-oriented rehabilitation, using measures like phytostabilization to reduce the mobility and bioavailability of toxic elements. Finally, biological rehabilitation aims to rebuild the fundamental life-supporting systems of the soil, such as nutrient cycling and organic matter content, which are often depleted in post-mining substrates.

To operationalize these responses, the report provides a catalogue of practices organized into ten categories. A practice is considered successful only when it directly addresses a diagnosed dysfunction and supports the intended long-term agricultural use. For example, the application of organic amendments like compost or biochar is a multifunctional intervention that can simultaneously improve soil structure, increase water-holding capacity, and stimulate microbial activity. However, the catalogue also warns against risky practices, such as routine deep loosening without confirmed compaction or the application of untested organic wastes, which may introduce secondary pollution. Monitoring remains essential, as visual greening does not always guarantee that the soil is safe or biologically mature.

Report present selected regional experiences from Poland, Czechia and Greece.

A key strategy proposed in COFA Project is the transitional use of energy crops. These perennial plants can serve as an intermediate stage in the reclamation process, providing multifunctional benefits such as carbon sequestration, stabilization of degraded substrates, and improvement of soil organic matter. This transitional phase allows land managers to reduce environmental risks and generate economic value while gradually preparing the land for eventual high-standard agricultural uses like food production. Ultimately, agricultural reclamation ends only when the land is successfully integrated into a stable, productive, and safe after-use.

1. INTRODUCTION

1.1. Background and rationale

Post-mining land degradation remains one of the key environmental and socio-economic challenges in European coal regions undergoing transition. Coal and lignite extraction alters landforms, removes or mixes soils, disrupts hydrological systems, reduces soil organic matter, and often creates substrates with poor fertility, compaction, erosion risk, acidity, salinity, or different contamination. As a result, post-mining areas frequently require not only physical stabilization, but also long-term soil regeneration before they can support productive and sustainable land uses. Within the COFA Project, this challenge is addressed through the proposing of transformation of degraded coal and lignite post-mining areas into productive agricultural landscapes, with particular attention to carbon farming, energy crops, and sustainable land-use scenarios (Maksymowicz et al., 2025).

The rationale for this Report is that agricultural reclamation cannot be treated as a single technical action or a universal land-use solution. The suitability of post-mining land for agricultural use depends on the type and severity of soil dysfunctions, the intended production pathway, the level of contamination risk, water availability, landform stability, and the feasibility of restoring soil functions over time. Therefore, the selection of reclamation and regeneration methods must be based on a diagnosis of soil limitations and on a realistic assessment of whether the land can support food crops, fodder production, grazing, industrial crops, energy crops, or transitional soil-building vegetation.

The COFA Project and this Report respond to this need by compiling and evaluating soil regeneration and agricultural reclamation practices that may be applied in post-mining areas. Its role is to identify methods that can restore or improve soil health, fertility, biological activity, water retention, and productive capacity, while also recognizing cases where agricultural use may be limited, conditional, or inappropriate. In this way, the task supports the COFA objective of moving beyond simple rehabilitation toward practical, site-sensitive and sustainable reclamation strategies for coal-transition regions.

1.2. Objectives

The main objective of COFA Task 3.3 (Analysis of soil regeneration and agricultural reclamation practices) is to compile, analyse, and evaluate existing soil regeneration and agricultural reclamation practices applicable to coal and lignite post-mining areas. The task focuses on measures that can improve soil structure, fertility, organic matter content, biological activity, hydrological functioning, vegetation establishment, and long-term land productivity. Particular attention is given to practices relevant to agricultural reclamation, including conventional agricultural use and alternative production pathways such as energy crops, industrial crops, biomass production, and carbon farming systems. The Report covers technical, biological, agronomic, remediation-related, and management-oriented measures that may support the recovery of soil functions and enable agricultural or biomass-oriented land use. It also considers the relationship between reclamation practices and future land-use pathways, including food production, fodder and grazing systems, industrial crops, energy crops and carbon farming.

A key objective is to assess the effectiveness and limitations of different reclamation and regeneration techniques under varied environmental, geological, and socio-economic conditions. The Report also contributes to the identification of good and bad or risky practice examples. Good practices are understood as approaches that are technically feasible, environmentally safe, compatible with the intended agricultural use, and capable of improving soil functions over time. Bad or risky practices include approaches that create unstable landforms, ignore key soil dysfunctions,

increase contamination pathways, produce unsafe biomass, fail to maintain soil cover, or result in short-term vegetation establishment without long-term soil recovery.

The analysis further recognises that agricultural reclamation is only one possible direction of post-mining land transformation. In some cases, forestry, hydrological reclamation, ecological succession, recreation, renewable energy infrastructure, conservation, or mixed-use development may be more appropriate. Therefore, while this Report focuses on agricultural reclamation and soil regeneration, it does not assume that agriculture is suitable for every post-mining site. Its purpose is to identify where and how agricultural reclamation can be technically, environmentally, and socially justified within the broader COFA framework, including the regional suitability assessment framework presented in the [COFA 3.1 Report](#).

Finally, the findings support the practical outputs of COFA by providing knowledge for integration into the Agricultural Toolkit development in COFA WP5. The toolkit is intended to support stakeholders in planning agricultural reclamation and carbon farming on coal post-mining land through a geodatabase, calculators, reports, guides, manuals, and scenario-based recommendations. The Report therefore serves both a scientific-review function and a practical decision-support function.

Because COFA includes case-study contexts in Czechia, Greece, and Poland, the analysis recognises that post-mining areas differ in climate, geology, mining history, substrate properties, water conditions, legal context, and land-use expectations. The Report therefore avoids one-size-fits-all recommendations and does not rank reclamation methods as universally good or bad. Instead, it evaluates practices in relation to the soil dysfunctions they address, the risks they may create, and the agricultural pathways for which they are intended. The findings are intended to support comparative assessment, guidance development, and later integration into COFA tools and scenarios, rather than to provide final site-specific engineering designs, detailed reclamation prescriptions, or legally binding reclamation plans. Detailed implementation will require site-specific investigation, including soil testing, contamination assessment, hydrological analysis, landform stability assessment, legal review, and consultation with relevant stakeholders.

1.3. Link with COFA 3.2 Report (Soil Dysfunction Classification Report)

This Report builds directly on the [COFA 3.2 Report](#) (Soil Dysfunction Classification Report) (Königová, et al., 2026), which developed a classification of soil dysfunctions in post-mining lands. That Report identified the main physical, hydrological, chemical, toxicological, and biological limitations affecting post-mining soils and explained how these dysfunctions constrain agricultural reclamation potential. This diagnostic framework is the starting point for this analysis, because regeneration measures can only be properly evaluated when they are linked to the specific soil problems they are intended to address.

In the logic of the Project, the [COFA 3.2 Report](#) explains why particular areas are constrained, while this Report focuses on how those constraints may be reduced, managed, or overcome through reclamation and soil regeneration practices. For example, erosion, compaction, acidity, salinity, contamination, low organic matter, nutrient deficiency, poor biological activity, and disturbed water regimes each require different interventions. This Report therefore uses the dysfunction categories from the [COFA 3.2 Report](#) as a basis for matching reclamation and soil rehabilitation techniques to soil limitations (*see section 3*) and for distinguishing good practices from ineffective or risky ones (*see sections 4-5*).

2. CONCEPTUAL FRAMEWORK

This section provides the terminology needed for the assessment of soil regeneration methods and agricultural reclamation practices in post-mining areas. Because the review gathers approaches from Czechia, Greece, and Poland, a shared conceptual framework is necessary to ensure that terms such as reclamation, remediation, soil rehabilitation, soil regeneration, revegetation, and post-mining development are used consistently. This is particularly important because the nomenclature used in post-mining land transformation is complex, often overlapping, and not always applied uniformly across scientific literature, national regulatory systems, and practical reclamation planning. Therefore, this Review continues and further develops the terminology and definitions proposed in the COFA 3.2 Report (Soil Disfunction Classification Report) (Königová, et al., 2026), where the conceptual basis for distinguishing soil dysfunctions, reclamation approaches, and post-mining land-use pathways was introduced.

Reclamation is understood here as a broad process of transforming degraded or post-mining land toward a defined future use, while agricultural reclamation is treated as one specific direction within this wider process. Particular attention is given to soil-related processes, because the main focus of Task 3.3 is the regeneration of soil functions needed for productive, safe, and sustainable agricultural use.

The chapter also clarifies the difference between technical, biological, legal, ecological, and developmental aspects of reclamation. This distinction supports the later evaluation of good and bad practices by showing that successful agricultural reclamation cannot be judged only by landform stability or vegetation cover, but must also consider soil quality, contamination risks, biomass pathways, long-term fertility, and suitability for the intended land use.

2.1. Reclamation

In the context of degraded and post-mining land, reclamation should be understood as an umbrella term describing the planned transformation of degraded, devastated, or disturbed land into a safe and functional landscape with a defined future use. It is not limited to soil improvement or agricultural recovery. Rather, reclamation may include landform shaping, slope stabilization, hydrological regulation, soil reconstruction, vegetation establishment, infrastructure preparation, landscape design, and risk reduction, depending on the intended reclamation direction. In Polish legal and scientific usage, reclamation is defined as the creation or restoration of utility or natural value of degraded or devastated land through appropriate land shaping, improvement of physical and chemical properties, regulation of water conditions, soil restoration, reinforcement of scarps, and construction or reconstruction of necessary access routes (Uberman et al., 2012; Kaźmierczak et al., 2017; Polish Geological and Mining Law Act, 2011; Gerwing et al., 2021; Tripathi et al., 2016).

This broad definition is important because reclamation can follow many directions, including agricultural, forestry, hydrological or water-based, recreational, ecological, industrial, cultural, infrastructural, or mixed-use directions. Polish studies of lignite mining show that reclaimed post-mining areas have been used for agriculture, forestry, water reservoirs, recreation, tourism, industrial functions, wind-energy infrastructure, and other special uses. Therefore, agricultural reclamation should be treated as one specific direction within the wider category of reclamation, not as the default meaning of reclamation itself (Kasztelewicz, 2014; Kaźmierczak et al., 2017; Pagouni et al., 2024; Wang et al., 2017; Zhang et al., 2018).

A useful definition for this report is therefore that reclamation is the planned technical, ecological, hydrological, and spatial transformation of degraded or post-mining land in order to restore or create a defined utility, natural, landscape, or socio-economic value. This definition is broad enough to

include agricultural reclamation, but also other reclamation pathways, including mixed-use post-mining landscapes (Każmierczak et al., 2017; Kasztelewicz, 2014; Gerwing et al., 2021).

2.1.1. Three-phase reclamation process

Soil regeneration in post-mining lands follows a structured, three-phase approach based on Polish standard PN-G-7800:2002. These interdependent phases include preparatory works, technical rehabilitation, and biological rehabilitation.

- Phase 1: preparatory works - integrated during the project design stage, this phase determines future land use through geological studies of local water bodies, soil properties, and land transformation. Critically, decisions are made regarding topsoil protection, specifically whether to remove and temporarily store the surface layer.
- Phase 2: technical reclamation - this phase establishes the engineered foundation through extensive earthwork. Key activities include landscaping, regulating water body interlinkages, restoring topsoil, and stabilizing slopes against erosion. According to Kasztelewicz (2010), a primary goal is creating a land relief that supports mechanized agrotechnical work while controlling groundwater levels.
- Phase 3: biological reclamation - this final phase restores soil fertility and protects reclaimed areas from erosion. It initiates natural soil-forming processes by introducing targeted vegetation. Because high biological activity requires abundant nutrients, the most critical task is enriching the reclaimed soil with organic matter and mineral fertilizers.

Reclamation must begin with the decision and planning of future land use. Because a mine's operational time is finite, legal requirements often mandate reclaiming the land to a useful economic or social state. These plans need to be outlined at the start of a mining project to ensure activities do not make future repurposing impossible. A good planning methodology takes reclamation and soil rehabilitation into account during the earliest steps of mine development. However, decades can pass between initial plans and the actual start of work. During this time, new technologies, legislation, or social needs may emerge. Consequently, constant monitoring of available technologies and possible land uses is an absolute necessity.

Earthworks for mine waste dumps must be tailored to the intended post-mining land use, with dumping optimized for future site reshaping. Initial assessments are necessary to evaluate material composition, acid-forming potential, and potential hazards, while site stabilization through slope reinforcement, drainage, or isolation is critical to manage risks of landslides and contamination. Mine reclamation must also manage hydrogeological impacts, which alter the levels, flow directions, and chemical composition of groundwater and surface water.

Topsoil management is the cornerstone of soil regeneration. The surface layer must support self-sustaining vegetation with proper infiltration, water capacity, aeration, rooting depth, plant nutrients, non-toxic salinity and pH levels, and necessary microorganisms. Topsoil should be retained and reused when overburden cannot form the basis for desired land use. Double topsoil removal, where the top 50 to 100 millimetres is removed and returned separately, maximizes the contribution of native seeds to post-mining flora (Grant et al., 2016).

The selection of plant species is determined by reclamation goals and intended land use. When substantial soil modification has occurred, a helpful approach is to search for local analogues of post-mining landscapes and use them as models. If natural counterparts cannot be found, species tolerant of the growing environment should be selected, or the growth medium must be managed, enriched, or fertilized to achieve rehabilitation goals.

Finally, the direction of reclamation is determined by factors including surrounding land use, climatic conditions, hydrological conditions, soil conditions, socio-economic factors, technical-economic factors, and technological feasibility (Cymerman, 1988). While natural factors like hydrology are decisive for certain uses, technical and economic factors prove most crucial in practice. Synthesizing various classification systems, Kasztelewicz (2010) summarized possible directions including agricultural, forestry, natural, recreational, aquatic, commercial, and cultural uses, each with specific applications ranging from crop production and timber to sports facilities, housing, and museums.

2.1.2. Reclamation directions

The direction of reclamation should be selected according to the physical, geological, hydrological, ecological, legal, economic, social, and planning conditions of the site. European and Polish studies emphasize that post-mining land-use planning should not rely on a single universal model; instead, the selected direction should match the site's morphology, contamination status, water conditions, surrounding land use, ownership, infrastructure, community needs, and long-term development potential (Pavloudakis & Roumpos, 2004; Pavloudakis et al., 2009; Pagouni et al., 2024; Uberman et al., 2012; Gerwing et al., 2021; Tripathi et al., 2016).

In Poland, the most frequently discussed directions include agricultural reclamation, forestry reclamation, hydrological reclamation, natural succession, recreational reclamation, and special or economic forms of reclamation (Table 1). For example, Polish lignite mines have used agricultural reclamation mainly in the Adamów and Konin mining areas, forestry reclamation in areas such as Turów and Bełchatów, hydrological reclamation through large post-mining reservoirs, and recreational or special development through ski slopes, harbours, tourist infrastructure, wind farms, industrial zones, and waste-management sites (Kasztelewicz, 2014; Kaźmierczak et al., 2017).

2.1.3. Technical reclamation and biological reclamation

Within the reclamation process, it is useful to distinguish technical reclamation and biological reclamation. Technical reclamation refers to the engineering and physical-preparation stage of reclamation. It includes landform shaping, backfilling, levelling, slope formation and stabilization, drainage and water regulation, covering or isolating unsuitable materials, preparation of the rooting layer, and construction or reconstruction of access roads. In Polish terminology, these activities correspond to the statutory understanding of reclamation as land shaping (Figure 1), water regulation, soil restoration, slope reinforcement, and road construction or reconstruction (Uberman et al., 2012; Kaźmierczak et al., 2017; Kirilov & Banov, 2016; Feng et al., 2019).

Biological reclamation refers to the soil- and vegetation-oriented stage of reclamation. It includes the introduction or support of vegetation, improvement of soil or soil-forming substrates, fertilization, liming, organic amendments, microbial recovery, erosion control through plant cover, and long-term development of soil functions. Biological reclamation is especially important in agricultural, forestry, grassland, and ecological reclamation directions because these uses require living soil systems capable of supporting roots, nutrient cycling, water retention, and stable vegetation cover (Sheoran et al., 2010; Kumari & Maiti, 2022; Kirilov & Banov, 2016; Mao et al., 2024).

The distinction between technical and biological reclamation is important because technical reclamation may make a site physically stable and legally prepared for use, while biological reclamation determines whether the land can support vegetation, soil development, and long-term ecosystem or agricultural functions. A post-mining area may therefore be technically reclaimed but still biologically immature if the substrate remains compacted, nutrient-poor, biologically inactive, acidic, contaminated, or unable to sustain the intended vegetation or crop system (Strzałkowski & Kaźmierczak, 2019; Feng et al., 2019; Haigh, 1995).

Table 1. Classification of reclamation directions according to objectives, soil rehabilitation role.

Reclamation direction	Main objective	Role of soil rehabilitation	Examples
Agricultural reclamation	Create land for crops, fodder, grazing, or biomass production.	Central - soil fertility, rooting depth, water retention, pH, organic matter, and contamination safety are critical.	Crops, grassland, pasture, energy crops, industrial crops.
Forestry / afforestation reclamation	Establish forest, protective woodland, timber production, or habitat.	Important - tree rooting, water supply, and long-term stand development matter most.	Pine, birch, black locust, spruce, native forestation, protective forest.
Hydrological / water reclamation	Transform pits, voids, or subsidence areas into lakes, reservoirs, wetlands, or water-management systems.	Secondary - focus is on water quality, hydrology, slope stability, shoreline safety, and landscape integration.	Pit lakes, reservoirs, wetlands, aquaculture, recreational water bodies.
Recreational reclamation	Create public, tourist, educational, or sport-oriented landscapes.	Variable - important for vegetation and safety, but not necessarily for agricultural productivity.	Parks, ski slopes, harbours, trails, geotourism, educational paths.
Ecological / succession reclamation	Restore habitats, biodiversity, wetlands, ecological succession, or landscape connectivity.	Important - but target is ecological function rather than crop yield.	Wetlands, wildlife habitats, spontaneous succession, native vegetation mosaics.
Industrial / infrastructural reclamation	Prepare land for industrial, technical, municipal, or infrastructure functions.	Limited - often to stabilization, drainage, contamination control, and safety.	Industrial parks, landfills, roads, wind farms, technical infrastructure.
Mixed-use reclamation	Combine several post-mining functions in one landscape.	Variable	Agriculture + forest + lake + recreation + conservation + energy infrastructure.

(Based on: Kasztelewicz, 2014; Psotová, 2023; Kivinen, 2017; Cinar & Ocalir, 2019; Pavloudakis et al., 2009).



Figure 1. Technical reclamation of the internal spoil heap of the Józwin open-pit mine. Source: [KWB Konin](#)

2.2. Soil rehabilitation, soil regeneration, and revegetation as distinct concepts within reclamation

The term soil rehabilitation is narrower than reclamation. It refers specifically to the recovery or improvement of soil functions required for a selected land use. In agricultural or forestry reclamation, soil rehabilitation may include improving soil structure, rooting depth, pH, nutrient availability, organic matter, microbial activity, water retention, and reduction of toxicity or contaminant bioavailability. Thus, soil rehabilitation is one possible component of reclamation, but it should not be treated as a synonym for reclamation as a whole (Kaźmierczak et al., 2017; Sheoran et al., 2010).

Soil regeneration is a stronger and longer-term concept than soil rehabilitation. Rehabilitation may make soil suitable for a planned use, whereas regeneration implies the progressive rebuilding of soil health, including organic carbon accumulation, biological activity, aggregation, nutrient cycling, vegetation-soil feedbacks, and resilience. Long-term studies of reclaimed mine lands show that soil quality may continue improving for decades after initial reclamation, especially under pasture, grassland, and forest vegetation, which supports the interpretation of regeneration as a long-term process rather than a one-time technical intervention (Hartati & Sudarmadji, 2022; Buta et al., 2019; Bandyopadhyay et al., 2020).

Revegetation is narrower still. It means the natural or assisted establishment of plant cover on disturbed land, for example through sowing, planting, spontaneous or directed succession, or other assisted natural recovery. Revegetation is often a key tool of biological reclamation because it reduces erosion, stabilizes the surface, adds organic matter, supports microbial recovery, and initiates soil-forming processes. However, revegetation alone does not prove that land is fully reclaimed, agriculturally productive, or safe for food or fodder production (Sheoran et al., 2010); Buta et al., 2019).

2.3. Remediation as a distinct concept within reclamation

Remediation refers to actions aimed at reducing, removing, immobilising, isolating, degrading, or otherwise controlling contaminants so that risks to human health, ecosystems, groundwater, surface water, crops, livestock, and future land users become acceptable. Unlike reclamation, which is a broad land-transformation process directed toward a future use, remediation is specifically concerned with pollution and exposure pathways. Therefore, remediation may be part of reclamation, but it is not identical with reclamation: a site may be technically reclaimed in terms of landform, drainage, and vegetation, but still require remediation if contaminants remain mobile, bioavailable, or capable of entering food chains or water systems (Vangronsveld et al., 2009; Newton et al., 2023; Kim et al., 2019; Peco et al., 2021).

In post-mining and brownfield contexts, remediation is required when contamination creates unacceptable risks for the intended after-use. This is especially relevant for former metal-processing sites, coal and lignite mining areas, sulphur mines, zinc and lead heaps, industrial spoil heaps, illegal landfills, contaminated sediments, and urban brownfields. Polish examples show that remediation may be necessary not only before agricultural use, but also before recreational, commercial, or urban development, because users may be exposed through direct soil contact, dust inhalation, groundwater contamination, plant uptake, or contaminated surface runoff (Likus-Cieřlik et al., 2017; Rostański, 2023; Newton et al., 2023; Rouhani et al., 2023; Thornton et al., 2008).

A useful definition for this report is that remediation is the set of technical, chemical, biological, or nature-based measures used to reduce contaminant concentrations, mobility, bioavailability, toxicity, or exposure pathways to a level compatible with the intended land use. This definition separates remediation from reclamation: reclamation answers the question “what function should the land have

after disturbance?”, whereas remediation answers the question “are contamination risks low enough for that function to be safe?” (Vangronsveld et al., 2009; Fernández-Braña et al., 2023; Mourinha et al., 2022).

2.3.1. Relationship between remediation and reclamation

Remediation and reclamation often overlap, but they have different primary objectives. Reclamation focuses on creating a stable, usable, and planned post-disturbance landscape, whereas remediation focuses on reducing contaminant-related risk. For example, a post-mining area may be reclaimed as a park, forest, reservoir, industrial site, or agricultural field, but the remediation requirements will differ depending on how people, plants, animals, water, and soil interact with contaminants under that use. Recreational reclamation may require preventing direct human contact with contaminated material, while agricultural reclamation requires much stricter control of contaminant uptake into edible crops, fodder, or grazing systems (Rostański, 2023; Newton et al., 2023; Kim et al., 2019).

This distinction is important for agricultural reclamation because visible revegetation or good biomass production does not necessarily mean that the site is safe. Plants may grow well while accumulating trace elements, and biomass from contaminated land may transfer metals into food, fodder, compost, ash, or industrial residues. Therefore, in agricultural reclamation, remediation must be evaluated not only by plant cover or yield, but also by contaminant mobility, bioavailability, plant uptake, biomass destination, and the exposure pathway created by the intended use (Śliwa-Cebula et al., 2022; Fernández-Braña et al., 2023; Khan et al., 2022; Evangelou et al., 2014).

2.3.2. Main remediation approaches relevant to reclamation

Remediation approaches can be grouped into removal, isolation, immobilisation, stabilisation, degradation, and biological or plant-based remediation. Removal includes excavation, relocation, disposal, or soil washing; isolation includes capping, sealing, barriers, geotextiles, liners, and hydraulic control; immobilisation and stabilisation reduce contaminant mobility or bioavailability using amendments such as lime, organic matter, biochar, phosphates, clay minerals, or other sorbents; degradation is mainly relevant for organic contaminants such as hydrocarbons; and biological remediation uses plants, microorganisms, or plant–microbe systems to extract, stabilise, transform, or degrade pollutants (Vangronsveld et al., 2009; Rouhani et al., 2023; Mourinha et al., 2022; Peco et al., 2021).

Polish case studies illustrate that remediation may involve strong engineering measures where contamination is severe. In Łomianki near Warsaw, remediation of an illegal landfill contaminated with arsenic and chromium involved relocation of hazardous material, waste segregation, bentonite mats, geotextiles, sand layering, drainage systems, and containment to prevent contaminant migration toward groundwater; post-remediation surveys reported major reductions in arsenic and chromium levels and improved structural stability. This example shows that remediation can be integrated with reclamation and later commercial development, but its primary purpose remains contaminant containment and risk reduction (Sobieraj & Metelski, 2025).

Other Polish examples show that remediation may also be necessary after apparently successful reclamation. At the former sulphur mine Jeziórko in southern Poland, reclamation was effective over much of the site, but local hotspots still had very high sulphur concentrations, extremely low pH, elevated electrical conductivity, and sulphate-rich waters. This demonstrates that reclamation and remediation should be assessed spatially: a site may appear reclaimed at landscape scale while still containing contaminant hotspots that require targeted remediation or long-term monitoring (Likus-Cieślik et al., 2017).

2.3.3. Phytoremediation

Phytoremediation is a nature-based remediation approach that uses plants and associated microorganisms to remove, contain, immobilise, transform, or degrade contaminants in soils, sediments, or shallow groundwater. The main mechanisms include phytoextraction, where contaminants are taken up into harvestable biomass; phytostabilization, where contaminants are immobilised in soil or roots; phytodegradation, where root-associated microorganisms degrade organic pollutants; rhizofiltration, where roots remove pollutants from water; and phytovolatilization, where contaminants are transformed and released in volatile form. European field experience shows that phytoremediation can be useful, but its success depends strongly on contaminant type, concentration, bioavailability, soil conditions, plant species, microbial interactions, climate, biomass handling, time scale, and economic feasibility (Vangronsveld et al., 2009; Laghlimi et al., 2015).

Phytomanagement is broader than phytoremediation. Instead of aiming only to remove contaminants, phytomanagement combines risk reduction, vegetation cover, ecosystem-service recovery, and sometimes safe biomass production. It is especially relevant for large, moderately contaminated brownfields and post-mining areas where complete excavation or soil replacement is technically difficult, economically unrealistic, or environmentally disruptive. In European brownfield contexts, phytomanagement with second-generation crops such as *Miscanthus* has been proposed as a way to combine remediation, biomass production, carbon sequestration, and economic reuse of marginal land (Newton et al., 2023; Hostyn et al., 2022; Moreira et al., 2021; Cundy et al., 2016).

The choice between phytoextraction and phytostabilization depends on contamination intensity and plant behaviour. A European brownfield study found that the same spontaneous species could show phytoextraction potential under lower contamination but phytostabilization behaviour under higher contamination, indicating that remediation strategy should be selected according to pollution degree rather than plant presence alone. This is important for agricultural reclamation because high biomass production does not automatically mean safe biomass production (Fernández-Braña et al., 2023; Khan et al., 2022).

Polish research on contaminated bottom sediments also shows both the potential and limits of phytoremediation. In a study using *Mesembryanthemum crystallinum* on metal-contaminated sediments from an industrial area in Poland, the plant accumulated several metals and reduced some metal concentrations, but plant growth and microbial activity could also increase toxicity under some substrate variants. This supports a cautious interpretation: phytoremediation should be monitored with chemical and ecotoxicological tests, not judged only by plant survival or metal uptake (Śliwa-Cebula et al., 2022).

2.3.4. Remediation in agricultural reclamation

In agricultural reclamation, remediation is especially important because the intended land use can create direct exposure pathways through crops, fodder, grazing animals, dust, irrigation water, and soil ingestion by livestock. Food-crop reclamation has the strictest remediation requirements because contaminants may enter edible plant parts and then the human food chain. Fodder and grazing systems also require strict control because contaminants can transfer from soil to forage and then to milk, meat, or animal organs. Therefore, agricultural reclamation of contaminated post-mining land should be based on risk assessment, contaminant bioavailability, crop uptake tests, and biomass-use restrictions rather than only on soil fertility or yield (Vangronsveld et al., 2009; Khan et al., 2022; Kim et al., 2019).

Where contamination prevents safe food or fodder production, remediation-oriented agricultural reclamation may instead use non-food pathways such as industrial crops, energy crops, fibre crops, aromatic plants, short-rotation coppice, or second-generation biomass crops. These systems can

reduce direct food-chain exposure while still providing vegetation cover, erosion control, carbon inputs, landscape improvement, and potential economic return. However, they still require management of harvested biomass, combustion ash, digestate, processing residues, and contaminant recycling back to soil (Newton et al., 2023; Hostyn et al., 2022; Khan et al., 2022; Perlein et al., 2021).

2.4. Reclamation and post-mining area development

Reclamation should also be distinguished from post-mining area development. In Polish legal and scientific terminology, reclamation refers to the restoration or creation of utility or natural value through technical, hydrological, soil, and infrastructural measures, whereas development refers to the subsequent agricultural, forestry, or other use of the reclaimed land. This distinction is important because a site may be legally reclaimed but not yet successfully developed, economically used, socially accepted, or integrated into local spatial planning (Uberman & Ostręga, 2012; (Kaźmierczak et al., 2017).

Post-mining development is therefore the longer-term implementation of the planned after-use. It may include farming, forestry, recreation, tourism, conservation, industrial redevelopment, renewable-energy infrastructure, water reservoirs, cultural functions, or mixed-use spatial development. Polish and European studies emphasize that successful post-mining development requires not only technical reclamation, but also legal clarity, spatial planning, infrastructure, ownership arrangements, economic feasibility, environmental safety, and social acceptance (Kasztelewicz, 2014; Pavloudakis et al., 2009; Kivinen, 2017; Servou et al., 2023; Kivinen et al., 2018; Svobodova, 2019).

Table 2. Key terms and definitions related to reclamation.

Term	Definition for this Report	Relationship to reclamation	Main indicators or examples
Reclamation	Umbrella process of transforming degraded or post-mining land into a safe and functional landscape with a defined utility, natural, landscape, or socio-economic value.	Broadest term; includes many directions, not only agriculture or soil repair.	Agriculture, forestry, water reservoirs, recreation, conservation, industry, infrastructure, mixed use.
Technical reclamation	Engineering and physical-preparation stage of reclamation.	Operational phase within reclamation.	Landform shaping, slope stabilization, drainage, water regulation, substrate preparation, roads.
Biological reclamation	Soil- and vegetation-based stage aimed at restoring biological productivity and ecological function.	Operational phase within reclamation, especially important for agricultural, forestry, and ecological directions.	Vegetation cover, soil amendments, microbial recovery, nutrient cycling, erosion control.
Remediation	Measures that reduce contaminant concentration, mobility, bioavailability, toxicity, or exposure pathways so that land can be safely used for its intended function.	May be part of reclamation, but is not identical with reclamation; it focuses on pollution risk rather than land-use creation or soil productivity alone.	Excavation, containment, capping, isolation, immobilisation, stabilisation, soil washing, phytoremediation, bioremediation, monitored natural attenuation, risk-based land-use restrictions.
Soil rehabilitation	Recovery of selected soil functions required for a planned use.	Component of reclamation, not a synonym.	pH, fertility, structure, rooting depth, organic matter, microbial activity, water retention.
Soil regeneration	Long-term rebuilding of soil health and self-sustaining soil functions.	Long-term outcome of successful biological reclamation or ecological recovery.	Organic carbon, aggregation, microbial activity, nutrient cycling, resilience, self-sustaining vegetation.
Revegetation	Natural or assisted establishment of plant cover on disturbed land.	Tool or component of biological reclamation.	Sowing, planting, spontaneous succession, erosion control, surface stabilization.
Post-mining development	Actual long-term use and management of reclaimed land.	Follows or overlaps with reclamation but is conceptually distinct.	Farming, forestry, recreation, reservoirs, industry, conservation, tourism, renewable energy.

(Based on: Uberman & Ostreĝa, 2012; Kaźmierczak et al., 2017; Kasztelewicz, 2014; Sheoran et al., 2010; Vangronsveld et al., 2009; Bandyopadhyay et al., 2020; Kivinen, 2017).

2.5. When reclamation ends

Technically, reclamation ends when the planned technical and biological works have been completed and the site meets predefined criteria for its intended use. For agricultural reclamation, this should include stable terrain, safe slopes, regulated water conditions, adequate rooting medium, improved soil physical and chemical properties, erosion control, and evidence that the land can support the intended agricultural pathway (Uberman & Ostręga, 2012; Sheoran et al., 2010; (Adesipo et al., 2021).

Legally, reclamation ends when the competent administrative authority confirms that the reclamation obligation specified in the relevant permit, decision, or reclamation plan has been fulfilled. In the Polish framework, this legal endpoint is connected to the statutory definition of reclamation as restoration or creation of utility or natural value through specified technical, hydrological, soil, and infrastructural measures (Polish Geological and Mining Law Act, 2011; Uberman & Ostręga, 2012; (Pagouni et al., 2024). Legal aspects of agricultural reclamation are being further investigated within COFA Project WP4.

Ecologically, reclamation may not truly “end” at the moment of legal acceptance. Soil formation, microbial recovery, organic matter accumulation, vegetation succession, and stabilization of nutrient cycles can continue for decades, as shown by long-term mine-land studies in which soil quality improved over 40 years under different vegetation covers (Buta et al., 2019; Bandyopadhyay et al., 2020; Noviyanto et al., 2017; Hartati & Sudarmadji, 2022).

Developmentally, reclamation ends only when the land is successfully integrated into a stable after-use, such as productive agriculture, grazing, biomass production, forestry, renewable energy, recreation, or conservation. This endpoint depends not only on soil and landform conditions, but also on ownership, infrastructure, markets, spatial planning, and local stakeholder acceptance (Kaźmierczak et al., 2017; Kivinen, 2017; Pavloudakis et al., 2009; Basu & Mishra, 2024).

Table 3. Proposed types of reclamation endpoints.

Endpoint	Meaning	Who usually verifies it?	Why it matters
Technical	Engineering, hydrological, soil-preparation and stabilization works are completed.	Engineers, reclamation specialists, inspectors, environmental authorities.	A site can be physically stable but not yet biologically mature.
Legal	Competent authority accepts that the reclamation obligation has been fulfilled.	Public administrative authority.	Legal acceptance may occur before long-term soil regeneration or successful agricultural use.
Ecological	Soil and vegetation functions become self-sustaining and resilient.	Long-term monitoring, scientists, land managers.	Ecological recovery may take decades after technical completion.
Development	The reclaimed land is actually used and managed successfully for its planned purpose.	Landowner, farmer, municipality, investor, conservation manager.	Reclamation can be legally complete but development can still fail.

(Based on: Pagouni et al., 2024; Uberman & Ostręga, 2012; Polish Geological and Mining Law Act, 2011; Sheoran et al., 2010; Adesipo et al., 2021; Buta et al., 2019; Bandyopadhyay et al., 2020; Kivinen, 2017; Pavloudakis et al., 2009).

3. AGRICULTURAL RECLAMATION AS ONE RECLAMATION DIRECTION

Within this broader framework, agricultural reclamation is one specific direction of reclamation in which the final or transitional land use is agricultural production or soil-building vegetation. It requires stronger attention to soil rehabilitation and soil regeneration than many other reclamation directions because the reclaimed land must support plant growth, rooting, water retention, nutrient cycling, and, in the case of food or fodder production, contaminant-free production. Agricultural reclamation may be appropriate where the post-mining substrate can be transformed into soil or soil-like material capable of supporting crops, grassland, grazing, or non-food biomass production (Kasztelewicz, 2014; Sheoran et al., 2010; Mensah, 2015).

Agricultural reclamation can be divided according to the intended biomass pathway. The most risk-sensitive category is food-crop reclamation, where crops enter the human food chain. Fodder and grazing reclamation also require strict assessment because contaminants may move from soil to forage and then into livestock products. Industrial and energy-crop reclamation may reduce direct food-chain exposure because biomass is used for fibre, bio-based materials, energy, or technical purposes, but these pathways still require assessment of contaminant uptake, biomass handling, processing residues, and ash or waste streams (Moreira et al., 2021; Saran et al., 2023; Slycken et al., 2013; Schröder et al., 2018).

A separate category is transitional soil-building reclamation, where grasses, legumes, cover crops, or early successional vegetation are used to stabilize the surface, increase organic matter, improve nitrogen cycling, reduce erosion, and prepare the land for later agricultural, forestry, or ecological use, as part of biological reclamation (*see section 2.1.3*). This staged approach is especially relevant for young technosols, post-mining heaps, and substrates that are not immediately suitable for intensive agriculture (Sheoran et al., 2010; Maiti, 2022; Mensah, 2015).

3.1. Types of agricultural reclamation

Agricultural reclamation can be classified according to the destination of biomass and the risk pathway. This is especially important in post-mining and contaminated areas because food crops, fodder, industrial crops, energy crops, and phytomanagement crops create different exposure pathways for humans, animals, soils, water, and biomass processing chains (Moreira et al., 2021; Saran et al., 2023; Robinson et al., 2009; Schröder et al., 2018). The COFA Team proposes the following classification (Table 4).

3.1.1. Food-crop reclamation

Food-crop reclamation is agricultural reclamation aimed at producing crops for direct human consumption or food processing, such as cereals, vegetables, potatoes, fruit, oilseed crops, or pulses. This is the strictest form of agricultural reclamation because contaminants can enter edible plant parts and then the human food chain. Food-crop reclamation requires more than successful plant growth. It requires evidence of safe contaminant levels, low bioavailability of potentially toxic elements, acceptable crop uptake, adequate soil fertility, controlled pH and salinity, good water relations, and compliance with food-safety standards. Reviews of trace-element-polluted soils emphasize that soil pollution can threaten food, fodder, and industrial crop production because trace elements persist and may accumulate through food chains (Saran et al., 2023; Agrelli et al., 2017).

Table 4. Proposed classification of types of agricultural reclamation.

Agricultural reclamation type	Definition	Main risk pathway	Suitable use conditions
Food-crop reclamation	Reclamation aimed at producing crops for direct human consumption or food processing.	Soil → edible plant parts → human food chain.	Only where contaminant bioavailability and crop uptake are low and soil quality is sufficient.
Fodder and grazing reclamation	Reclamation aimed at producing pasture, hay, silage, or feed crops for livestock.	Soil → forage → animals → milk/meat.	Requires safe forage quality, low contaminant transfer, and controlled soil ingestion by livestock.
Industrial-crop reclamation	Reclamation aimed at non-food biomass for fibre, oil, aromatic crops, construction materials, or bio-based products.	Soil → harvested biomass → processing residues or products.	Useful where food production is unsuitable but controlled non-food biomass production is possible.
Energy-crop reclamation	Reclamation aimed at producing biomass for heat, electricity, biogas, biofuel, or other energy uses.	Soil → biomass → combustion, digestion, ash, or residues.	Suitable for marginal or contaminated land if biomass and residues are safely managed.
Phytomanagement reclamation	Plant-based management of contaminated land to reduce pollutant linkages, stabilize contaminants, restore ecosystem services, and sometimes produce non-food biomass.	Designed to avoid or control exposure pathways.	Suitable where food/fodder production is unsafe but vegetation can reduce risk and improve ecosystem services.
Transitional soil-building reclamation	Temporary use of grasses, legumes, cover crops, or early successional vegetation to build soil before final use.	Depends on whether biomass is removed, grazed, or left in place.	Suitable for young Technosols, mine spoils, erosion-prone substrates, and low-organic-matter soils.

(Based on: Kasztelewicz, 2014; Sheoran et al., 2010; Maiti, 2022; Moreira et al., 2021; Burges et al., 2018; Slycken et al., 2013).



*Figure 2. Barley cultivation area in the Wielkopolskie Voivodeship, Poland.
Source: Marshal Office of the Wielkopolskie Voivodeship*

3.1.2. Fodder and grazing reclamation

Fodder and grazing reclamation is agricultural reclamation aimed at producing hay, silage, pasture, or feed crops for livestock such as cattle, sheep, goats, or horses. This category is still part of the food chain because contaminants may move from soil to forage, from forage to animals, and then into milk, meat, or other animal products. Compared with vegetable or direct food-crop production, grassland and pasture reclamation may sometimes be more suitable for young or marginal reclaimed soils because perennial cover reduces erosion, improves organic matter inputs, supports microbial activity, and stabilizes the surface. A 40-year retrospective study in Romania found that pasture and natural grassland covers significantly improved soil quality in abandoned mine lands, including microbial activity and nutrient status (Buta et al., 2019).



*Figure 3. Cultivation of alfalfa (*Medicago sativa*).
Source: Świat Kwiatów*

3.1.3. Industrial-crop reclamation

Industrial-crop reclamation uses reclaimed land to produce non-food biomass for fibre, oil, construction materials, bio-based products, or other industrial uses. Examples include Industrial hemp (*Cannabis sativa* L.), Flax (*Linum usitatissimum* L.), fibre crops, aromatic crops, oil crops cultivated for technical applications, and other non-edible industrial crops.. This pathway can be useful where food production is restricted by contamination risk or low soil quality. Industrial crops can reduce food-chain risk because the biomass is not intended for direct human or animal consumption, but they still require environmental assessment. Contaminants may be transferred into harvested biomass, processing residues, combustion ash, composts, or industrial by-products, so non-food use does not automatically mean risk-free use. Reviews of phytomanagement and post-phytoremediation biomass emphasize that contaminated biomass must be managed carefully to avoid secondary pollution (Bert et al., 2026; Moreira et al., 2021; Khan et al., 2022).



Figure 4. Cultivation of industrial hemp (*Cannabis sativa* L.).
Source: [MojaRola](#)

3.1.4. Energy-crop reclamation

Energy-crop reclamation is a subcategory of industrial reclamation in which biomass is produced for heat, electricity, biogas, biofuels, or other energy uses. Common examples include Willow (*Salix* spp.), Poplar (*Populus* spp.), Miscanthus (*Miscanthus × giganteus*), Reed canary grass (*Phalaris arundinacea*), Switchgrass (*Panicum virgatum*), and other perennial biomass crops.. Energy crops are often discussed for marginal, contaminated, or post-industrial lands because they may combine biomass production with soil cover and phytomanagement. Energy crops can be beneficial because perennial root systems stabilize soil, reduce erosion, add organic matter, and may support phytostabilization. However, degraded soil conditions can limit biomass yield, and contaminated biomass or ash may require special management. Recent phytomanagement studies therefore

frame energy crops as both a biomass-production option and a nature-based remediation strategy, but not as a universal solution (Bert et al., 2026).



*Figure 5. Basket willow (*Salix viminalis* L.) cultivated as an energy crop.
Source: [Instsani.pl](https://www.Instsani.pl)*



*Figure 6. Mechanical harvesting of energy willow (*Salix viminalis* L.).
Source: [Instsani.pl](https://www.Instsani.pl)*

3.1.5. Phytomanagement

Phytomanagement is the use of plants to manage contaminated or degraded soils while potentially producing useful non-food biomass. Unlike conventional food-crop reclamation, the main goal is not necessarily maximum yield, but reduction of exposure pathways, stabilization of contaminants, erosion control, improvement of soil functions, and safe biomass valorisation where possible. Phytomanagement is especially relevant where land is too contaminated for food or fodder production but still suitable for controlled non-food biomass, aromatic crops, fibre crops, or energy crops, including Industrial hemp (*Cannabis sativa* L.), Basket willow (*Salix viminalis* L.), Poplar (*Populus spp.*), and Miscanthus (*Miscanthus × giganteus*). Reviews describe phytomanagement as a restorative and circular bioeconomy approach, but they also emphasize that field-scale evidence remains limited and that biomass management is a critical unresolved issue. (Saran et al., 2023; Moreira et al., 2021; Burges et al., 2018).

3.1.6. Transitional agricultural reclamation

Transitional agricultural reclamation uses temporary vegetation or crops to build soil before final land use is attempted. This may include legumes, grasses, grass-legume mixtures, cover crops, green manure, or early successional vegetation. In mine-land reclamation, nitrogen-fixing legumes, grasses, herbs, and trees are frequently used because they stabilize soil, add organic matter, improve nutrient cycling, and support microbial recovery. This category is important because young technosols or mine spoils may not be immediately suitable for intensive agriculture. A staged approach - first stabilization, then soil-building vegetation, then controlled agricultural use - is more scientifically defensible than immediate food production on newly reclaimed land (Maiti, 2022; Sheoran et al., 2010; Boldt-Burisch et al., 2015).



Figure 7. Cultivation of phacelia (*Phacelia tanacetifolia* Benth.) as a catch crop.
Source: [Świat Kwiatów](#)

3.2. Specific requirements of agricultural reclamation

Agricultural reclamation is more demanding than simple revegetation because the reclaimed land is expected not only to support plant cover, but also to sustain safe, productive, and manageable agricultural use. In this context, vegetation establishment is only an initial condition. Agricultural reclamation additionally requires sufficient rooting depth, favourable soil structure, adequate fertility, stable water availability, limited contamination risks, and long-term capacity to maintain crop or biomass production. These requirements are especially important in post-mining soils, where soil horizons are often removed, mixed, compacted, chemically altered, biologically depleted, or contaminated (Sheoran et al., 2010; Haigh, 1995; Feng et al., 2019; Vangronsveld et al., 2009; Moreira et al., 2021).

Below, the COFA consortium proposes a list of general requirements of agricultural reclamation:

- food and feed safety,
- limited contaminant uptake by crops and biomass,
- sufficient rooting depth and favourable soil physical conditions,
- adequate soil fertility and biological activity,
- stable water availability and suitable hydrological functioning,
- suitability for agricultural machinery and field operations,
- long-term productivity rather than short-term establishment,
- compliance with environmental and agricultural standards,
- monitoring of soil and plant quality.

In summary, agricultural reclamation should be understood as a higher-standard reclamation pathway than simple revegetation, natural succession or erosion control. It requires a reconstructed soil system that is physically workable, chemically fertile, biologically active, hydrologically functional, safe for the intended biomass pathway, and capable of maintaining productivity over time (Sheoran et al., 2010; Vangronsveld et al., 2009; Moreira et al., 2021).

Regional suitability for agriculture is addressed separately in the [COFA 3.1 Report](#). This section focuses on the soil-related and use-related requirements that must be met once agricultural reclamation is considered a possible land-use direction.

3.2.1. Food and feed safety

The first requirement is food and feed safety. If reclaimed land is intended for food crops, fodder, grazing, or any biomass entering the food chain, the soil-plant system must not create unacceptable exposure pathways for humans or animals. This means that total contaminant concentrations alone are insufficient; contaminant mobility, bioavailability, plant uptake, and transfer into edible or feed biomass must also be assessed. European experience from contaminated and reclaimed mine sites shows that amendments and revegetation may improve fertility and reduce metal mobility, but residual trace elements may still require long-term monitoring, especially where crops, fodder, or human access are involved (Madejón et al., 2018; Fernández-Caliani et al., 2021; Garau et al., 2021).

3.2.2. Limited contaminant uptake by crops and biomass

A second requirement is limited contaminant uptake by crops and biomass. This is particularly relevant for potentially toxic elements such as Cd, Pb, Zn, Cu, As, Hg, Ni, Cr, and other site-specific contaminants associated with mining, waste rock, tailings, ash, or industrial deposits. For food and

feed production, contaminant uptake must remain below applicable safety thresholds. For non-food biomass, such as energy crops or industrial crops, uptake may be more acceptable, but it still requires control of harvested biomass, processing residues, ash, digestate, or re-application pathways. Studies from European contaminated sites show that phytostabilization, organic amendments, lime, compost, biosolids, and other amendments can reduce metal mobility and plant uptake, but effectiveness depends on contaminant type, soil pH, organic matter, amendment properties, and long-term stability (Vangronsveld et al., 2009; Madejón et al., 2018; Brown & Chaney, 2016; Novak et al., 2019).

3.2.3. Sufficient rooting depth and favourable soil physical conditions

A third requirement is sufficient rooting depth and favourable soil physical conditions. Agricultural reclamation requires a reconstructed soil profile or rooting medium deep enough to support the intended crops, store water, allow aeration, and permit root penetration. Excessive compaction, high bulk density, coarse fragments, poor aggregation, surface crusting, and shallow rooting layers can restrict crop growth even when chemical fertility appears adequate. Soil quality standards proposed for reclaimed coal-mine lands identify compaction as one of the key constraints and suggest that bulk density should be controlled within the upper soil profile to protect long-term productivity (Haigh, 1995; Sheoran et al., 2010; Feng et al., 2019).

3.2.4. Adequate soil fertility and biological activity

A fourth requirement is adequate soil fertility and biological activity. Reclaimed mine soils often have low organic matter, low nitrogen and phosphorus availability, weak cation exchange capacity, poor microbial activity, and limited nutrient cycling. Agricultural reclamation therefore requires measures that rebuild soil fertility, including topsoil replacement where available, organic amendments, composts, manure, biosolids where legally acceptable, liming, fertilisation, cover crops, legumes, and gradual development of soil organic carbon. European mine-site studies show that lime, composted biosolids, organic amendments, and vegetation can improve pH, cation exchange capacity, base saturation, available phosphorus, soil organic carbon, microbial biomass, and plant establishment, but long-term monitoring is needed to confirm durable soil recovery (Fernández-Caliani et al., 2021; Larney & Angers, 2012; Garau et al., 2021; Myszura-Dymek & Żukowska, 2023).

3.2.5. Stable water availability and suitable hydrological functioning

A fifth requirement is stable water availability and suitable hydrological functioning. Agricultural reclamation depends on the ability of the reconstructed soil and landform to retain water, drain excess water, avoid prolonged waterlogging, and reduce drought stress. Post-mining areas may have disrupted drainage, compacted layers, altered groundwater levels, high runoff, erosion, salinity, or acid drainage. Therefore, agricultural reclamation must ensure that the soil profile and terrain support water infiltration, storage, and controlled drainage. Reviews of coal-mine reclamation emphasize hydrological stability as one of the core phases of pot-mining soil reconstruction, alongside geomorphic reshaping, soil reconstruction, vegetation restoration, and landscape rebuilding (Feng et al., 2019; Sheoran et al., 2010; Haigh, 1995).

3.2.6. Suitability for agricultural machinery and field operations

A sixth requirement is suitability for agricultural machinery and field operations. Agricultural land must be trafficable, safe, and workable under normal management conditions. This requires appropriate slope gradients, surface stability, absence of excessive stones or obstacles, controlled erosion risk, adequate bearing capacity, and field layouts compatible with cultivation, sowing, harvesting, grazing management, or biomass removal. If the landform is technically stable but too steep, irregular,

compacted, wet, stony, or erosion-prone, it may support vegetation but still be unsuitable for agricultural reclamation (Haigh, 1995; Feng et al., 2019). This requirement links technical reclamation with later agricultural development and should be distinguished from broader regional suitability assessment, which is addressed separately in the [COFA 3.1 Report](#).

3.2.7. Long-term productivity rather than short-term establishment

A seventh requirement is long-term productivity rather than short-term establishment. Agricultural reclamation should not be judged only by early plant cover or initial biomass yield. Reclaimed mine soils often develop slowly, and their physical, chemical, and biological properties may continue changing for years or decades. Chronosequence studies and long-term reclamation assessments show that soil quality, organic carbon, aggregation, nutrient cycling, and biological activity may improve with reclamation age, but reclaimed soils can remain below reference conditions for long periods. Therefore, agricultural reclamation should include long-term indicators of productivity, resilience, and soil health rather than relying only on first-year vegetation success (Fernández-Caliani et al., 2021; Feng et al., 2019; Ippolito et al., 2024).

3.2.8. Compliance with environmental and agricultural standards

An eighth requirement is compliance with environmental and agricultural standards. Agricultural reclamation must comply with applicable soil protection, water protection, waste-use, fertiliser, food safety, feed safety, nature protection, and agricultural management requirements. This is especially important where amendments such as compost, sewage sludge, industrial by-products, ash, lime, or other secondary materials are used. Such materials may improve soil fertility and immobilise contaminants, but they may also introduce salts, metals, organic pollutants, pathogens, or nutrient leaching risks if poorly selected or applied. Therefore, reclamation materials and agricultural outputs should be assessed according to both agronomic benefits and environmental safety (Garau et al., 2021; Larney & Angers, 2012; Peter et al., 2024).

3.2.9. Monitoring of soil and plant quality

Finally, agricultural reclamation requires monitoring of soil and plant quality. Monitoring should include physical indicators such as bulk density, aggregation, rooting depth, erosion, and infiltration; chemical indicators such as pH, electrical conductivity, organic carbon, nutrients, cation exchange capacity, salinity, acidity, and contaminant concentrations; biological indicators such as microbial activity, soil respiration, enzyme activity, soil fauna, and vegetation performance; and crop or biomass indicators such as yield, contaminant uptake, feed or food safety, and residue quality. Polish and European post-mining studies show that monitoring soil, plant, and water chemistry is essential because reclaimed sites may contain local contamination hotspots or delayed risks even where reclamation appears generally successful (Sheoran et al., 2010; Madejón et al., 2018; Pietrzykowski & Likus-Cieślak, 2018; Feng et al., 2019).

4. FROM SOIL DYSFUNCTION TO AGRICULTURAL RECLAMATION PRACTICE

The COFA 3.2 Report (Soil Dysfunction Classification Report) (Königová, et al., 2026) provided the diagnostic foundation for the present chapter by reviewing the main soil dysfunctions occurring in landscapes affected by coal and lignite mining. It showed that post-mining land degradation is multidimensional and cannot be reduced to a single problem of poor vegetation cover, low fertility or lack of agricultural productivity. Instead, mining-affected soils may suffer from a combination of physical, hydrological, chemical, contamination-related and biological dysfunctions, as well as broader forms of post-mining land degradation that extend beyond soil properties alone. This perspective is essential for this report, because agricultural reclamation should not begin with the automatic selection of a standard technique, but with the identification of the specific soil dysfunctions that limit safe and productive land use.

In the COFA 3.2 Report, the main soil dysfunctions were grouped into five principal categories. Physical dysfunctions included erosion, soil compaction and disruption of soil structure. Hydrological dysfunctions included infiltration disruption and decreased water retention capacity. Chemical dysfunctions included unfavourable chemical conditions, with particular attention to acidification and salinization. Contamination was treated as a separate category because pollutants may create specific risks for soil, water, vegetation, food/feed production and human or animal exposure. Biological dysfunctions included nutrient deficits, loss of organic matter and loss of soil organisms. In addition, the COFA 3.2 Report recognised that post-mining degradation may also include forms of land degradation beyond soil dysfunctions, such as landform instability, altered landscape structure, loss of previous land-use functions and limitations for future land development.



Figure 8. Soil Dysfunction Classification Framework developed within the COFA project.

This chapter uses the COFA 3.2 Report typology as a bridge between diagnosis and practice. The central assumption is that each diagnosed dysfunction defines a different reclamation objective. For example, erosion requires surface stabilisation and permanent or semi-permanent vegetation cover; compaction requires restoration of porosity, aeration and rooting conditions; soil structure disruption requires rebuilding aggregation and a functional rooting medium; infiltration and retention problems require improvement of soil-water relations; salinization requires chemical and hydrological correction; contamination requires risk assessment and, where necessary, remediation; while nutrient deficits, organic matter loss and loss of soil organisms require long-term rebuilding of fertility and biological activity. Therefore, agricultural reclamation is treated here not as a single intervention, but as a sequence of technical, biological, chemical, hydrological and management measures adjusted to the diagnosed dysfunctions (Königová et al., 2026; Sheoran et al., 2010; Feng et al., 2019).

This dysfunction-based approach is particularly important for agricultural reclamation, which is more demanding than simple revegetation or landscape stabilisation. Land intended for agricultural use must not only support plant cover, but also provide sufficient rooting depth, adequate fertility, stable water availability, safe contaminant levels, acceptable trafficability for agricultural machinery and long-term productive capacity. Where food or feed production is planned, additional requirements apply, including control of contaminant uptake by crops, protection of livestock and compliance with environmental and agricultural standards. In this sense, the same post-mining area may be suitable for non-food biomass production, energy crops, fibre crops, grazing, arable production or only restricted agricultural use, depending on the severity and combination of soil dysfunctions.

The Polish experience from the Konin lignite mining region illustrates why such a diagnostic approach is necessary. Studies from this region show that the agricultural potential of post-mining grounds depends strongly on overburden composition, selective or non-selective dumping, technical land shaping, soil compaction, water conditions, organic matter development and the duration of post-reclamation management. In the Kleczew municipality, opencast lignite mining caused substantial transformation of land use and soil cover, including the destruction of naturally developed agricultural soils and the creation of anthropogenic post-mining soils, some of which were later returned to agricultural production after reclamation (Kozłowski et al., 2024). Similarly, research from the Konin area shows that physical improvement of post-mining soils may be slow and that several years of reclamation may not be sufficient to fully restore favourable soil structure and water relations (Stachowski, 2006; Stachowski & Szafrański, 2006; Otremba, 2011).

The following sections therefore translate the soil dysfunction framework proposed in the COFA 3.2 Report, into practical agricultural reclamation responses. For each dysfunction category, the chapter identifies the main reclamation objective, suitable practices, risky or poor practices and key monitoring indicators.

For clarity, soil dysfunctions are presented in the table below (Table 5). This structure also helps avoid treating agricultural reclamation as a generic set of techniques. Instead, it supports a problem-oriented approach in which the selected practice depends on the diagnosed dysfunction, the intended agricultural pathway, the safety requirements for food or feed production, and the long-term monitoring needs of reclaimed post-mining land.

Table 5. Soil dysfunctions summary from the [COFA 3.2 Report](#) and relevance for this Report.

Dysfunction category	Specific dysfunctions COFA Report D3.2	Relevance COFA Report 3.3
Physical dysfunctions	Erosion; soil compaction; soil structure disruption; examples of physical dysfunctions in study areas.	Determine whether reclaimed land can support rooting, infiltration, aeration, machinery use and stable agricultural management.
Hydrological dysfunctions	Infiltration disruption; decreased retention capacity; examples of hydrological dysfunctions in study areas.	Determine water availability, drought/waterlogging risk, runoff, drainage needs and long-term crop performance.
Chemical dysfunctions	General chemical dysfunctions; salinization; examples of salinization in study areas.	Determine pH, salinity, nutrient availability, amendment needs, phytotoxicity risk and crop suitability.
Contamination	Contamination and examples of contamination in study areas.	Determines whether agricultural use is safe, whether remediation is needed, and whether food/feed production should be restricted or replaced by non-food uses.
Biological dysfunctions	Nutrient deficits; loss of organic matter; examples of nutrient deficits; loss of soil organisms; examples of biological dysfunctions in experimental sites.	Determine the need for rebuilding fertility, organic carbon, microbial activity, soil fauna and long-term biological soil functions.
Other post-mining land degradation beyond soil dysfunctions	Broader degradation forms beyond soil properties.	Important for distinguishing soil regeneration from wider post-mining land development, including landscape stability, land-use planning and future functionality.

(Based on: [COFA 3.2 Report](#) (Soil Dysfunction Classification Report - Königová, et al., 2026).

4.1. Soil rehabilitation practices for physical dysfunctions

Physical dysfunctions identified in the [COFA 3.2 Report](#) include erosion, soil compaction and soil structure disruption. In post-mining landscapes, these dysfunctions are often caused by topsoil removal, overburden excavation, dumping, grading, heavy machinery traffic and the lack of stable vegetation cover. For agricultural reclamation, physical rehabilitation is fundamental because it determines whether the reconstructed soil can support rooting, infiltration, aeration, trafficability and long-term cultivation. Polish studies from the Konin lignite mining region show that post-mining substrates may have high bulk density, low porosity, weak aggregation and strong spatial heterogeneity, while physical improvement may require long-term soil-forming processes rather than only short-term technical works (Stachowski, 2006 ;Otremba, 2011). Broader reviews of coal mine reclamation similarly emphasise that stripping, dumping and random soil reconstruction increase small-scale heterogeneity and affect physical, chemical and biological soil properties (Feng et al., 2019; Larney & Angers, 2012).

The main objective of rehabilitation in physically degraded post-mining soils is to reconstruct a functional rooting medium and stabilise the land surface. This requires not only terrain shaping, but also improvement of soil structure, reduction of compaction, protection against erosion and gradual development of aggregation. In agricultural reclamation, these measures should be planned with future machinery use in mind, because a technically stabilised surface may still be unsuitable for farming if slopes are too steep, bearing capacity is poor, stoniness is excessive or subsoil compaction restricts root growth and water movement (Haigh, 1995; Stachowski, 2006; Otremba, 2011).

Recommended rehabilitation practices identified in reclamation literature include selective soil handling, reduction of compaction, terrain reshaping, erosion control, organic amendments and rapid revegetation (Sheoran et al., 2010; Feng et al., 2019; Larney & Angers, 2012; Mensah, 2015).

Possible rehabilitation practices for physical dysfunctions include:

- selective soil handling and reconstruction, including topsoil replacement where suitable material is available;
- selective placement of favourable overburden materials and terrain reshaping to create stable and cultivable landforms;
- alleviation of soil compaction through targeted deep loosening and reduced machinery pressure;
- addition of organic amendments to improve aggregation, water retention and biological activity;
- establishment of deep-rooting vegetation, grasses, legumes and cover crops to support soil formation and erosion control;
- rapid surface stabilisation using revegetation, mulching and other erosion-control measures.

These practices are widely recommended in mine-land reclamation literature and should be selected according to the substrate properties, slope conditions and intended agricultural pathway (Feng et al., 2019; Sheoran et al., 2010; Larney & Angers, 2012; Haigh, 1995).

To reduce erosion specifically, the priority is rapid surface stabilisation. Bare post-mining substrates are vulnerable to water and wind erosion because they often lack organic matter, aggregation and vegetation cover. Good practice therefore includes early revegetation, slope shaping, surface roughening, mulching and the use of grasses or legume-grass mixtures (Mensah, 2015; Sheoran et al., 2010). On steep or unstable slopes, agricultural use may be inappropriate (see the [COFA 3.1 Report](#)) and forest, grassland or nature-oriented reclamation may be safer. This is consistent with

the Konin experience, where agricultural reclamation was more suitable on dumping ground plateaus, while slopes were often directed towards forest reclamation (Stachowski, 2006).

To reduce soil compaction, rehabilitation should be based on diagnosis rather than routine deep loosening. Research from reclaimed post-mining areas shows that several years of agricultural reclamation may improve the upper soil layer while deeper layers may remain compacted or poorly permeable, meaning that subsoil compaction can remain hidden below an apparently improved topsoil (Stachowski, 2006; Haigh, 1995). Therefore, subsoiling, ripping or mechanical loosening should be applied only where penetration resistance, bulk density or infiltration measurements confirm the presence of compacted layers. Mechanical loosening should then be combined with biological measures, because without roots, organic matter and reduced traffic, the soil may reconsolidate. Several reviews emphasise that mechanical decompaction alone is often temporary unless combined with organic matter inputs, vegetation establishment and reduced traffic pressure (Larney & Angers, 2012; Mensah, 2015).

To improve soil structure, the most important long-term practice is rebuilding aggregation. Organic matter inputs, root growth, microbial activity and reduced disturbance are essential for transforming loose or compacted spoil into a more stable soil-like material (Larney & Angers, 2012; Mensah, 2015). Otremba (2011) showed that clear improvement of physical properties in post-mining soils may become visible only after long-term agricultural use, which confirms that soil structure rehabilitation is a gradual process (Otremba, 2011). Reviews also indicate that microbial processes are important for aggregate formation and that biological recovery should be integrated with physical reclamation (Larney & Angers, 2012).

Theoretically, poor practices in physical soil rehabilitation could include random overburden dumping, shallow reconstruction of the rooting layer, excessive grading that creates compacted surfaces, leaving bare slopes exposed to erosion, using heavy machinery on wet reclaimed soils and declaring land agriculturally suitable without testing compaction and rooting depth (Feng et al., 2019; Haigh, 1995).

4.2. Soil rehabilitation practices for hydrological dysfunctions

Hydrological dysfunctions identified in the COFA 3.2 Report include infiltration disruption and decreased retention capacity. In post-mining landscapes, these dysfunctions may result from altered landforms, compaction, poor soil structure, disrupted groundwater systems, low organic matter content and limited vegetation cover. Hydrological soil rehabilitation is important for agricultural reclamation because crops require both sufficient plant-available water and protection against waterlogging, runoff and drought stress.

In this context, the objective of soil rehabilitation is to restore functional soil–water relations by improving infiltration, increasing water retention, reducing excessive runoff and ensuring that reconstructed soils can store and supply water to crops. In agricultural reclamation, hydrological measures must be coordinated with physical rehabilitation because compaction and poor structure strongly affect infiltration (Feng et al., 2019; Sheoran et al., 2010).

Possible rehabilitation practices for hydrological dysfunctions include:

- reconstruction of a sufficiently deep and permeable rooting zone;
- alleviation of compacted layers that restrict infiltration;
- addition of organic amendments to improve aggregation and water retention;
- establishment of vegetation cover and deep-rooting plants to increase infiltration and reduce runoff;
- drainage or small-retention measures where waterlogging or drought risks are significant;

For infiltration disruption, rehabilitation should focus on removing barriers to water entry and movement. Surface crusting, compaction and low macroporosity reduce infiltration and increase runoff. Organic amendments, revegetation and deep-rooting plants can gradually improve infiltration, while compacted subsoil layers may require targeted loosening followed by biological stabilisation (Hu et al. 2024; Back et al. 2024).

For decreased retention capacity, the priority is rebuilding organic matter and improving soil structure. Post-mining substrates often contain little organic carbon and weak aggregation, reducing their capacity to store plant-available water. Organic amendments, composts, cover crops and perennial legumes can gradually improve water retention and soil quality. Reviews of former mining sites show that organic amendments can improve soil carbon, nutrient availability, pH and vegetation establishment, although amendment quality and contamination risks must be controlled where agricultural use is planned (Singh et al. 2022; Hu et al. 2024; Prescott et al. 2019).

Theoretically, poor practices in soil rehabilitation in relation to hydrology could include shaping land without considering runoff, leaving compacted subsoil layers, installing drainage without understanding site water balance and introducing water-demanding crops before soil water relations stabilise. Monitoring should include infiltration rate, groundwater level, soil moisture, runoff, waterlogging frequency, retention capacity and crop water response.

4.3. Soil rehabilitation practices for chemical dysfunctions

Chemical dysfunctions identified in the [COFA 3.2 Report](#) include acidification, salinization and broader chemical limitations affecting soil fertility and plant growth. In post-mining soils, these dysfunctions may involve unfavourable pH, salinity, nutrient imbalance, low cation exchange capacity and phytotoxic concentrations of selected elements. Such conditions influence nutrient availability, amendment requirements and the safety of agricultural use. In the Konin region, the chemical variability of post-mining materials is strongly linked to overburden composition and dumping methods, making soil testing essential before selecting reclamation measures (Stachowski, 2006; Otremba, 2011).

The main objective of chemical rehabilitation is to create a chemically stable rooting environment that supports plant growth without causing phytotoxicity, nutrient deficiency or excessive contaminant mobility. In agricultural reclamation, this requires more precise management than simple revegetation because crops may enter food, feed or biomass chains.

Possible rehabilitation practices for chemical dysfunctions include:

- soil testing before amendment application;
- pH correction through liming or acidifying measures where needed;
- improvement of salinity or sodicity through drainage, leaching or gypsum application;
- use of organic amendments to improve nutrient retention and cation exchange capacity;
- balanced fertilisation and phased introduction of crops adapted to site conditions;
- long-term monitoring of pH, salinity, nutrients and plant response.

To reduce salinization, rehabilitation should combine hydrological and chemical measures because salt leaching is effective only where drainage conditions are adequate. Reviews of salt-affected land reclamation emphasise that reclamation strategies must be site-specific and may combine leaching, amendments and salt-tolerant vegetation (Shaygan & Baumgartl, 2022).

For acidic or metal-rich substrates, rehabilitation often aims to reduce metal mobility and phytotoxicity through pH correction, amendments and vegetation establishment. Studies from mining-affected soils in the Iberian Pyrite Belt show that low pH, poor fertility and elevated trace

element concentrations frequently occur together, making combined chemical and biological rehabilitation necessary (Mourinha et al., 2022).

Theoretically, poor practices in soil rehabilitation in relation to chemical dysfunctions could include applying amendments without soil diagnosis, introducing chemically unstable wastes, ignoring salinity or pH constraints and assuming that vegetation cover alone confirms agricultural suitability.

4.4. Soil rehabilitation and remediation practices for contamination

The COFA 3.2 Report treated contamination as a separate dysfunction category because pollutants create risks that differ from ordinary fertility or structure problems. In post-mining landscapes, contamination may involve potentially toxic elements, acid mine drainage residues, hydrocarbons, salts or industrial wastes. For agricultural reclamation, contamination is especially important because pollutants may enter crops, livestock, groundwater, dust and biomass pathways. Therefore, contaminated post-mining soils require remediation-oriented rehabilitation rather than simple revegetation.

The main objective is to reduce contaminant mobility, bioavailability, plant uptake and exposure pathways. In agricultural reclamation, food and feed production should not be introduced until soil and plant testing confirm acceptable risk levels. Where risks remain, non-food pathways such as energy crops, fibre crops or phytostabilisation vegetation may be more appropriate (*see chapter 9*). Reviews of phytoremediation show that plant-based remediation can reduce contaminant mobility or uptake, but its effectiveness depends strongly on contaminant chemistry, soil conditions, amendments and biomass management (Chafik et al. 2025; Szmelich & Lazar, 2024).

Possible rehabilitation and remediation practices for contaminated post-mining soils include:

- site-specific contamination assessment and soil testing;
- immobilisation or stabilisation using amendments such as lime, phosphates, biochar or compost;
- phytostabilisation or other plant-based remediation approaches;
- restriction of food and feed production where contaminant uptake risks remain;
- use of non-food biomass crops where safe agricultural production is not possible;
- long-term monitoring of soil, plants, groundwater and dust.

For metal-contaminated soils, phytostabilisation is often more realistic than phytoextraction, especially over large areas. Combined use of vegetation and amendments can reduce contaminant mobility while improving soil conditions and erosion control (Mourinha et al., 2022; Sarathchandra et al., 2023).

Theoretically, poor practices in soil rehabilitation in relation to contamination could include cultivating food crops without testing, assuming that vegetation cover confirms safety, applying contaminated amendments and ignoring biomass, dust or groundwater pathways. Monitoring should include contaminant concentrations, bioavailability, plant uptake, groundwater quality and potential transfer to animals or humans.

4.5. Soil rehabilitation practices for biological dysfunctions

Biological dysfunctions identified in the COFA 3.2 Report include nutrient deficits, loss of organic matter and loss of soil organisms. These dysfunctions are especially important for agricultural reclamation because biological recovery determines whether post-mining substrates can gradually develop into functioning soils. Biological dysfunctions are closely linked to physical, hydrological and chemical limitations, since compacted, dry, acidic or contaminated substrates usually show weak microbial activity, poor root development and limited nutrient cycling (Sheoran et al. 2010).

The main objective of biological rehabilitation is to rebuild soil organic matter, nutrient cycling, microbial activity and stable plant–soil interactions. In the Konin reclamation model, legumes and grasses played an important role in early biological recovery, but long-term soil development still required continued management and biomass input (Stachowski, 2006).

Possible rehabilitation practices for biological dysfunctions include:

- application of safe organic amendments such as compost or manure;
- use of legumes, grasses and cover crops to support nitrogen cycling and soil stabilisation;
- return of crop residues and maintenance of continuous vegetation cover;
- diverse crop rotations and reduced disturbance where feasible;
- long-term monitoring of soil organic carbon, nutrients and biological activity.

For nutrient deficits, rehabilitation should combine mineral fertilisation with long-term organic matter rebuilding. Organic amendments improve nutrient availability, aggregation and microbial activity, while long-term fertility depends on continuous biomass input and biological development (Clayton et al. 2021; Miu et al. 2022).

Rehabilitating soils depleted of organic matter requires sustained carbon inputs via compost, manure, and crop residue. In drained hydrogenic soils, increased aeration may accelerate organic matter mineralisation, making water management and carbon protection especially important (Clayton et al. 2021).

To limit loss of soil organisms, rehabilitation should create conditions that support recolonisation by microbes, fungi and soil fauna through organic matter input, stable moisture, reduced toxicity and permanent vegetation cover. Reviews of post-mining rehabilitation emphasise that microbial processes are essential for nutrient cycling and spoil-to-soil transformation (Clayton et al. 2021; Miu et al. 2022).

Theoretically, poor practices in soil rehabilitation in relation to biological dysfunctions could include relying only on mineral fertilisers, removing all biomass without return, using contaminated amendments and judging success only by vegetation cover. Monitoring should include soil organic carbon, nutrients, microbial activity, vegetation performance and crop productivity.

4.6. Rehabilitation practices for other forms of post-mining land degradation beyond soil dysfunctions

The [COFA 3.2 Report](#) also recognised that post-mining degradation may extend beyond soil dysfunctions to include unstable landforms, disrupted landscape structure, poor accessibility, safety risks and limitations for future land use. These issues are important because agricultural reclamation cannot succeed if the wider post-mining landscape is unstable, inaccessible or incompatible with agricultural management.

The main objective is therefore to integrate soil rehabilitation with landform design, land-use planning and post-mining development. A site may show improving soil properties but still remain unsuitable for agriculture because of slope, fragmentation, poor access or surrounding land-use conflicts. Conversely, technically accessible land may still be unsuitable for food or feed production because of contamination or poor fertility.

Possible rehabilitation practices include:

- stabilisation of slopes and landforms;
- creation of field layouts and access suitable for agricultural machinery;
- drainage and erosion-control measures;

- zoning of land according to soil quality, safety and agricultural suitability;
- designation of unstable or high-risk areas for forest, grassland or biodiversity functions;
- long-term monitoring of slope stability, erosion and agricultural usability.

In the Polish context, formal reclamation and later agricultural development may occur as separate stages (see *sections 2.4-2.5*). Stachowski (2006) noted that vegetation cover may be treated as sufficient for formal reclamation even though the longer process of rebuilding productive agricultural soil continues afterwards. Similarly, studies from the Kleczew area showed that reclamation enabled some anthropogenic soils to return to agricultural use, but that mining also caused major long-term changes in land use and soil cover (Kozłowski et al., 2024).

Theoretically, poor practices could include treating land shaping and seeding as the end of reclamation, assigning steep or unstable slopes to agriculture and transferring land without long-term monitoring or management obligations.

4.7. Soil rehabilitation practices summary

The rehabilitation of post-mining soils for agricultural reclamation should be addressing the dysfunctions diagnosed in the COFA 3.2 Report. Physical dysfunctions require reconstruction of soil structure, rooting depth and surface stability. Hydrological dysfunctions require restoration of infiltration, retention and drainage. Chemical dysfunctions require correction of pH, salinity, sodicity and nutrient imbalances. Contamination requires risk-based remediation and may restrict food or feed production. Biological dysfunctions require long-term rebuilding of organic matter, nutrient cycling and soil life. Broader post-mining degradation requires landform stabilisation, zoning and integration with future land-use planning. Summary of key soil rehabilitation practices described in this section is presented in the table below (Table 6).

This approach supports the development of the best and worst practice catalogue in this Report (see *section 5*). A good practice is not simply a technique that produces vegetation cover - it is a practice that addresses the diagnosed dysfunction, supports long-term soil regeneration, reduces environmental and food/feed safety risks and is compatible with the intended agricultural pathway. A poor practice is one that creates superficial greening while leaving unresolved compaction, hydrological dysfunction, contamination, low fertility or land-use constraints. This is why agricultural reclamation should be assessed as a staged and monitored process rather than as a one-time intervention.

Table 6. Summary of key soil rehabilitation practices.

Dysfunction category	Main rehabilitation objective	Examples of suitable practices	Main risks if poorly addressed
Physical dysfunctions	Rebuild rooting medium, structure, porosity and surface stability.	Selective material placement, terrain shaping, decompaction, organic amendments, cover crops, erosion control, controlled traffic, forming a surface layer of mining waste without excessive compaction	Persistent compaction, erosion, poor rooting, machinery limitations, unstable yields.
Hydrological dysfunctions	Restore infiltration, retention, drainage and plant-available water.	Organic matter rebuilding, subsoil loosening, drainage regulation, water retention measures, cover crops, runoff control.	Drought stress, waterlogging, runoff, poor crop performance, secondary salinization.
Chemical dysfunctions	Correct pH, salinity, sodicity and nutrient imbalances.	Liming, gypsum, salt leaching where feasible, balanced fertilisation, organic amendments, tolerant transitional crops.	Phytotoxicity, nutrient deficiency, salinity persistence, contaminant mobilisation.
Contamination	Reduce contaminant mobility, uptake and exposure pathways.	Risk assessment, immobilisation, phytostabilization, phytoextraction with biomass control, bioremediation, non-food crops.	Food/feed contamination, unsafe grazing, contaminated biomass, groundwater or dust exposure.
Biological dysfunctions	Rebuild organic matter, nutrient cycling, microbial activity and soil fauna.	Compost, manure, green manure, legumes, grass-legume mixtures, residue return, reduced tillage, microbial support.	Superficial greening, low fertility, weak soil formation, poor resilience.
Other post-mining degradation	Integrate soil recovery with stable landform and future land use.	Slope stabilisation, zoning, access roads, field layout, drainage infrastructure, buffer zones, long-term planning.	Agricultural use on unsuitable land, safety risks, poor accessibility, failed land development.

(Based on: Stachowski, 2006; Otremba, 2011; Sheoran et al. 2010; Feng et al., 2019; Mourinha et al., 2022; Clayton et al. 2021; Miu et al. 2022)

5. CATALOGUE OF SOIL REGENERATION AND AGRICULTURAL RECLAMATION PRACTICES

Section 4 presented soil regeneration and agricultural reclamation from the perspective of diagnosed soil dysfunctions. Its logic was problem-oriented and it started from the identified soil dysfunctions - physical, hydrological, chemical, contamination-related and biological dysfunctions, as well as broader forms of post-mining land degradation. Then it discussed which types of rehabilitation or remediation measures may respond to each of them. In other words, the previous section answered the question:

“What type of intervention is needed when a specific soil dysfunction is present?”

This approach is necessary because post-mining soils are highly heterogeneous and the same reclamation method may be effective, insufficient or risky depending on the dominant limitation, substrate properties, hydrological conditions and intended agricultural use.

This section uses a different, practice-oriented logic. Instead of starting from soil dysfunction categories, it organises the content around the main types of soil rehabilitation, regeneration, and agricultural reclamation practices that can be applied on post-mining land. Therefore, the key question changes to:

“What does a given practice do and when is it useful?”

This structure is intended to make the review more operational for practitioners and the later COFA WP5 Agricultural Toolkit.

This distinction is important because many reclamation practices address more than one soil dysfunction.

For example, organic amendments may improve soil structure, water retention, nutrient supply, microbial activity and, in some cases, reduce metal bioavailability. However, they may also create risks if the amendment is contaminated, saline or applied without quality control.

Similarly, vegetation establishment may reduce erosion, support organic matter accumulation and improve biological activity, but it does not automatically prove that the land is safe for food or feed production. For this reason, this section of the Report treats each practice as a multi-functional intervention that must be matched with site diagnosis, agricultural pathway and monitoring requirements.

The intention of the Catalogue is therefore to be an operational translation of previous reviews. Each practice is described according to its main purpose, relevant soil dysfunctions, possible applications in agricultural reclamation, limitations, risks and monitoring indicators.

The practices included in this COFA Catalogue are grouped into 10 main categories:

- **soil reconstruction and substrate management,**
- **terrain shaping and erosion control,**
- **decompaction and physical soil improvement,**
- **organic matter rebuilding and biological activation,**
- **fertility restoration and chemical correction,**
- **water management and retention improvement,**
- **salinity and sodicity management,**
- **remediation and contaminant-risk reduction,**
- **revegetation and crop establishment,**
- **regenerative agricultural management (after reclamation).**

These categories are practice-based rather than dysfunction-based, but they remain linked to the discussed dysfunction framework through the assessment of which soil limitations each practice can address. For consistency, each practice category is discussed using the following structure (Tables 7-16):

- **main purpose of the practice;**
- **soil dysfunctions addressed,**
- **possible technical or biological measures,**
- **suitability for agricultural reclamation pathways, including food, feed, grazing, industrial crops, energy crops or restricted agricultural use,**
- **conditions under which the practice is recommended,**
- **conditions under which the practice may be insufficient or risky,**
- **monitoring indicators needed to verify effectiveness,**
- **relevance for good and bad practice assessment.**

This structure reflects the central assumption that a practice should be considered good only when it responds to the diagnosed dysfunction, improves soil functions, reduces environmental or food/feed safety risks, and supports the intended agricultural use over time.

Conversely, a practice may become poor or risky when it is applied without diagnosis, without monitoring, or without considering contamination, hydrology, soil development stage or agricultural end-use.

Table 7. COFA Catalogue of soil regeneration and agricultural reclamation practices - soil reconstruction and substrate management

Reclamation/rehabilitation practice	Main purpose of the practice	Soil dysfunctions addressed	Examples of technical or biological measures	Suitability for agricultural reclamation pathways	Conditions under which the practice is recommended	Conditions under which the practice may be bad, insufficient or risky	Monitoring indicators needed to verify effectiveness	Relevance for good and bad practice assessment
soil reconstruction and substrate management	<p>Soil reconstruction and substrate management are among the first and most decisive stages of agricultural reclamation on post-mining land.</p> <p>Their main purpose is to create a physically stable, chemically safe and biologically developable soil that can support vegetation establishment and, in later stages, agricultural use.</p> <p>In mining, natural soil profiles are often removed, mixed, or replaced by heterogeneous overburden materials. Consequently, the reconstructed substrate frequently differs from natural soil in texture, structure, organic matter content, and nutrient status.</p> <p>The objective is not just to cover the surface, but to reconstruct a functional soil profile suitable for the intended after-use. This involves providing sufficient rooting depth, acceptable texture, favourable pH and salinity conditions, and low contaminant risk.</p> <p>It is considered one of the core phases of soil recovery.</p>	<p>Physical: shallow rooting depth, high stoniness, compaction, and unsuitable for plant growth soil structure</p> <p>Hydrological: texture and layering determine infiltration and water retention.</p> <p>Chemical: it can reduce or aggravate issues depending on whether the reconstructed layer contains acidic, alkaline, or saline materials.</p> <p>Biological: the substrate determines if organic matter accumulation and microbial activity can occur.</p> <p>Contamination: if acid-generating or contaminated materials are placed in the rooting zone, it becomes a risk-control issue.</p>	<ul style="list-style-type: none"> ➢ Stripping and separate storage of topsoil before mining. ▪ Separate handling of topsoil, subsoil, and overburden. ▪ Forming a surface layer of dump without excessive compaction ➢ Protection of stored topsoil against erosion and compaction. ➢ Direct placement of topsoil where possible to avoid long storage. ➢ Selective placement of suitable overburden in the future rooting zone. ➢ Creation of a clean cover layer over unsuitable or contaminated substrates. ➢ Construction of technosols or artificial soil profiles. ➢ Zoning of substrates according to agricultural potential and risk. ➢ Removal or burial of stones below the rooting zone. ➢ Incorporation of clean organic amendments. ➢ Early establishment of vegetation to stabilize substrates. ▪ Laboratory phytotoxic testing before agricultural use. 	<p>Food Production: Has the strictest requirements, needing a deep, fertile rooting layer, low contaminant availability, and verified crop safety.</p> <p>Feed/Grazing: Also requires strict control as contaminants can enter the livestock food chain.</p> <p>Industrial/ Energy Crops: May tolerate poorer fertility or moderate contamination, but substrate safety and machinery access still matter.</p> <p>Staged Approach: Often recommended, starting with protective vegetation to build organic matter before introducing demanding food crops.</p>	<p>This practice is recommended whenever the original soil profile has been severely disturbed and the future land use is agricultural.</p> <p>It is particularly recommended when:</p> <ul style="list-style-type: none"> • uncontaminated topsoil is available, • overburden materials differ in suitability, • specific materials (saline, acidic, stony) must be excluded from the rooting zone, • a clean cover layer is needed to separate crops from contaminants, • early placement decisions will strongly affect long-term success. 	<p>Reconstruction alone is insufficient if it is not followed by biological reclamation and monitoring. It may look suitable immediately but still lack structure and microbial activity.</p> <p>Risks include:</p> <ul style="list-style-type: none"> • random dumping of overburden, • use of contaminated or chemically unstable substrates, • compaction caused by heavy machinery during grading, • impermeable layers causing waterlogging, • storing topsoil for long periods, which degrades biological quality. 	<p>Monitoring must verify if the substrate functions as a soil.</p> <p>Exemplary monitoring indicators include:</p> <ul style="list-style-type: none"> • physical (thickness of rooting layer, bulk density, porosity, aggregate stability, infiltration, water holding capacity). • chemical (pH, electrical conductivity, available NPK, cation exchange capacity). • biological/Agricultural (organic carbon, microbial activity, root penetration depth, crop yield, and contaminant uptake). <p>Monitoring should be repeated over time because reconstructed soils continue to develop after placement.</p>	<p>Good Practice: Selective material handling, sufficient rooting depth, clean substrates, and matching the soil to the intended agricultural pathway.</p> <p>Conditional: When topsoil is unavailable but alternative materials can be used safely after testing and amendment.</p> <p>Bad/risky Practice: Random dumping, using untested/contaminated materials, creating shallow/compacted layers, or transferring land to use without verifying safety.</p> <p>In summary, this practice forms the foundation of agricultural reclamation. If poorly designed, later interventions may only mask deeper, failure-prone limitations.</p>

(Based on: Buta et al., 2019; Chen et al., 2023; Fernández-Caliani et al., 2021; Gunathunga et al., 2023; Lu et al., 2024; Mao et al., 2024; Murawska-Włodarczyk et al., 2025; Mytsyk et al., 2024; Peñaranda Barba et al., 2023; Spargo & Doley, 2016; Yang et al., 2025).

Table 8. COFA Catalogue of soil regeneration and agricultural reclamation practices – terrain shaping and erosion control

Reclamation/rehabilitation practice	Main purpose of the practice	Soil dysfunctions addressed	Examples of technical or biological measures	Suitability for agricultural reclamation pathways	Conditions under which the practice is recommended	Conditions under which the practice may be bad, insufficient or risky	Monitoring indicators needed to verify effectiveness	Relevance for good and bad practice assessment
terrain shaping and erosion control	<p>Terrain shaping and erosion control is a critical component of technical reclamation. It ensures the physical and hydrological stability of the post-mining landscape, providing a framework for all subsequent biological and agricultural activities.</p> <p>The primary goal is to create stable, geomorphologically and hydrologically functional landforms that resist erosion and allow for proper drainage. In an agricultural context, this means ensuring the land is trafficable for machinery and can support long-term cultivation or grazing without losing the reconstructed soil layer to wind or water.</p>	<p>Physical: surface instability, excessive slope gradients, and water erosion.</p> <p>Hydrological: runoff concentration, low infiltration, and waterlogging in depressions.</p> <p>Biological/Chemical (indirectly): preventing erosion stops the removal of fine particles, organic matter, and nutrients, and reduces the risk of transporting contaminants via sediment to surrounding water bodies.</p>	<ul style="list-style-type: none"> ➢ Grading and reshaping of dumps, heaps and excavation areas. ➢ Reduction and stabilization of slope angles. ➢ Contour shaping, terracing and runoff control. ➢ Construction of drainage systems, waterways and retention structures. ➢ Protection of reconstructed topsoil against erosion and wash-off. ▪ Mulching and surface roughening to improve stability and water retention. ➢ Rapid establishment of grasses, legumes, cover crops and perennial vegetation. ➢ Use of soil bioengineering measures (e.g. vegetated strips, live barriers). ▪ Allocation of unstable slopes to non-arable uses such as grassland, shrubby vegetation or forestry. ➢ Maintenance of drainage infrastructure and access roads. 	<p>Food Production: Best suited for relatively gentle slopes with stable soil layers and low erosion risk to accommodate annual tillage and machinery.</p> <p>Feed/Grazing: Requires stable surfaces and established vegetation to prevent damage from livestock trampling; steep or erosion-prone areas may require restricted stocking densities.</p> <p>Industrial/ Energy Crops: Perennial energy crops are highly useful on moderately sloping land because their permanent root systems and continuous cover provide better erosion protection than annual crops.</p>	<p>The practice is particularly recommended when:</p> <ul style="list-style-type: none"> • spoil heaps or dumps have steep or irregular slopes, • slopes are long and uniform, increasing runoff velocity, • bare substrates are exposed to rainfall or wind, • reconstructed soil layers are at risk of wash-off, • rills, gullies or sediment movement are visible, • runoff concentrates in uncontrolled pathways, • depressions create waterlogging or ponding, • slope instability or mass movement is possible, • future agricultural machinery access is limited, • the site requires division into arable, grassland, protective or non-agricultural zones, • erosion may transport contaminated sediments. 	<p>Specific risky conditions include:</p> <ul style="list-style-type: none"> • creating long, smooth slopes without runoff breaks, • leaving bare soil exposed after grading, • using heavy machinery on wet reconstructed soils, • compacting the surface during final shaping, • placing topsoil on unstable or steep slopes without protection, • designing drainage without sediment control; • allowing runoff to discharge onto unprotected surfaces, • introducing annual arable crops before erosion risk is reduced, • allowing grazing before vegetation and soil are stable, ▪ Failure to consider the final land use in slope design • treating slope greening as proof of long-term stability. 	<p>Exemplary monitoring indicators include:</p> <ul style="list-style-type: none"> • physical stability - slope angle/slope length, and signs of rill or gully formation. • hydrological - infiltration rates, runoff pathways, and sediment accumulation at drainage outlets. • agricultural readiness - vegetation cover percentage, root development on slopes, and practical accessibility for agricultural machinery. 	<p>Good Practice: Integrated planning where landform design, drainage, and machinery access are coordinated, and steep areas are assigned appropriate low-intensity functions like grassland.</p> <p>Conditional: Terrain is stable but supports only limited pathways (e.g., permanent forage rather than annual food crops).</p> <p>Bad/risky Practice: Creating visually smooth but hydrologically unstable surfaces, ignoring runoff concentration, or introducing intensive grazing or tillage before the soil and vegetation are stable.</p> <p>In short, terrain shaping and erosion control provide the physical and hydrological framework for all later agricultural reclamation practices. If landforms are stable and erosion is controlled, soil reconstruction, organic matter rebuilding and crop establishment can proceed more effectively. If landforms are poorly designed, later biological and agronomic measures may be repeatedly undermined.</p>

(Based on: Martin-Moreno et al., 2016; Chen et al., 2017; Zhang et al., 2015; Hancock et al., 2003; Feng et al., 2019; Loch, 2000; Zapico et al., 2018).

Table 9. COFA Catalogue of soil regeneration and agricultural reclamation practices - decompaction and physical soil improvement

Reclamation/rehabilitation practice	Main purpose of the practice	Soil dysfunctions addressed	Examples of technical or biological measures	Suitability for agricultural reclamation pathways	Conditions under which the practice is recommended	Conditions under which the practice may be bad, insufficient or risky	Monitoring indicators needed to verify effectiveness	Relevance for good and bad practice assessment
decompaction and physical soil improvement	<p>The primary goal of decompaction and physical soil improvement is to restore the physical functionality of reconstructed post-mining soils.</p> <p>Its objective is not simply to loosen the soil mechanically, but to rebuild a physically functional rooting environment.</p> <p>This involves reducing excessive soil strength and bulk density to improve macroporosity, increase infiltration and drainage, and support deep root penetration.</p> <p>For agricultural reclamation, a functional profile must allow roots to explore the soil, air to circulate, and water to drain, while also enabling machinery to operate without causing immediate re-compaction.</p> <p>To be effective and durable, this practice must be integrated with biological stabilization, such as organic matter inputs and vegetation with strong root systems.</p>	<p>Physical: targets excessive compaction, high bulk density, poor soil structure, low macroporosity, and restricted rooting depth.</p> <p>Hydrological: addresses restricted infiltration that may lead to surface runoff, erosion risk, and water ponding; compacted layers often cause both drought stress and waterlogging.</p> <p>Biological/Chemical: indirectly supports recovery by improving aeration and rooting conditions, which stimulate microbial activity, organic matter decomposition, and nutrient cycling.</p>	<ul style="list-style-type: none"> Forming a surface layer of dump without excessive compaction Diagnosis and monitoring of soil compaction. Deep ripping, subsoiling or chisel ploughing where compaction is confirmed. Loosening of compacted subsoil before topsoil replacement where feasible. Timing of mechanical loosening under suitable soil moisture conditions. Restriction of heavy machinery operations on wet soils. Incorporation of organic amendments to improve aggregation and structure. Use of deep-rooting crops, perennial grasses and grass-legume mixtures. Mulching and residue return to support soil structure formation. Gradual transition to regular agricultural tillage after soil stabilisation. 	<p>Food Production: Highest importance; these crops require a well-structured rooting zone for stable yields, and unresolved compaction leads to poor establishment and drought sensitivity.</p> <p>Feed/ Grazing: May be needed during establishment, but grazing must be delayed until soil structure and vegetation are stable.</p> <p>Industrial/ Energy Crops: Supports the establishment of deep-rooting perennials or short-rotation coppice, though harvesting machinery impacts must still be planned.</p>	<p>This practice is recommended:</p> <ul style="list-style-type: none"> when diagnostic measurements confirm that compaction is the primary factor limiting root growth, infiltration, or crop performance. where compacted layers were created during technical stages like soil grading or replacement. where water accumulates above subsoil layers or roots are concentrated only in the shallow topsoil. when mechanical loosening can be immediately followed by biological stabilization (vegetation) and strict traffic control. 	<p>Decompaction is insufficient:</p> <ul style="list-style-type: none"> if it only addresses symptoms but not causes (e.g., continuing uncontrolled machinery traffic), or if poor growth is actually caused by other soil dysfunction. 	<p>To ensure improvements persist, monitoring should cover both the surface and subsoil over several seasons:</p> <ul style="list-style-type: none"> Physical - bulk density and penetration resistance by depth, total/macroporosity, and aggregate stability, water holding capacity. Hydrological - infiltration rate, saturated hydraulic conductivity, and runoff occurrence. Agricultural - root penetration depth/distribution, crop emergence, and yield stability. Operational - machinery trafficability and signs of re-compaction. 	<p>Good Practice: Characterized by diagnosis-based intervention, technical timing matched to moisture levels, follow-up biological stabilization, and integration with controlled traffic.</p> <p>Conditional: When decompaction is necessary but must be combined with chemical correction (e.g., for salinity or acidity) to be effective.</p> <p>Bad/risky Practice: Under unsuitable moisture conditions, on steep erosion-prone slopes; immediate re-compaction through uncontrolled heavy machinery.</p> <p>In short, decompaction it is often a necessary step where post-mining soils have been physically degraded by heavy machinery, grading and spoil reconstruction. Its success depends on appropriate timing, integration with biological soil-building measures.</p>

(Based on: Ning et al., 2022; Back et al., 2024; Miguel et al., 2023; Shrestha et al., 2009; Keller et al. 2021; Vanderhasselt et al., 2024; Bohrer et al., 2017; Varela et al. 2025).

Table 10. COFA Catalogue of soil regeneration and agricultural reclamation practices - organic matter rebuilding and biological activation

Reclamation/rehabilitation practice	Main purpose of the practice	Soil dysfunctions addressed	Examples of technical or biological measures	Suitability for agricultural reclamation pathways	Conditions under which the practice is recommended	Conditions under which the practice may be bad, insufficient or risky	Monitoring indicators needed to verify effectiveness	Relevance for good and bad practice assessment
organic matter rebuilding and biological activation	<p>The main purpose of organic matter rebuilding and biological activation is to restore the living and soil-forming functions of post-mining soils. This practice aims to increase soil organic carbon (SOC), improve nutrient cycling, and stimulate microbial and faunal activity. In many post-mining landscapes, natural topsoil is absent or degraded, leaving mineral substrates that are "biologically immature". Adding organic materials acts as a bridge between technical reclamation and biological soil development, accelerating the formation of a functional soil profile that can sustain agricultural production.</p>	<p>Biological: directly targets the loss of organic matter, low microbial biomass, weak nutrient cycling, and poor biological resilience.</p> <p>Chemical: improves fertility by supplying NPK and micronutrients, increasing cation exchange capacity (CEC), and improving nutrient retention.</p> <p>Physical: promotes aggregation, reduces surface crusting, and increases porosity.</p> <p>Hydrological: increases water-holding capacity and reduces vulnerability to surface sealing and runoff.</p> <p>Contamination: can reduce the bioavailability of certain metals through pH adjustment, sorption, or complexation.</p>	<ul style="list-style-type: none"> Application of compost from green waste or clean organic residues. Use of manure or slurry where legally and agronomically justified. Application of sewage sludge compost or biosolids, provided they meet strict quality standards. Use of soil improvers that combine organic materials from composts or sewage sludge with mineral components like fly ash. Application of biochar to improve long-term carbon stability, water retention, and sorption. Incorporation of crop residues and use of mulch to protect the surface. Establishment of grass-legume mixtures, cover crops, and green manures. Use of deep-rooting perennial plants to increase belowground carbon input. Inoculation with mycorrhizal fungi or beneficial microorganisms. Support of soil fauna recovery, specifically earthworms. Staged application of amendments rather than a single excessive dose. 	<p>Food Production: Requires the strictest control; only clean, legally compliant, and contaminant-free amendments should be used to ensure food safety.</p> <p>Feed/ Grazing: Caution is necessary because contaminants can enter livestock through forage or direct soil ingestion; safety must be verified before grazing begins.</p> <p>Industrial/ Energy Crops: Highly suitable as transitional soil-building systems; perennial energy crops can produce large biomass and root inputs to rebuild SOC.</p>	<p>This practice is recommended whenever post-mining soils biologically inactive. Specific recommended conditions include:</p> <ul style="list-style-type: none"> where soil organic carbon and microbial/enzyme activity are low. when topsoil is absent, diluted, or has been stored for long periods. where soil structure is weak, massive, or prone to surface sealing. as a necessary follow-up to technical reclamation to ensure the mineral substrate transforms into a functioning soil. 	<p>Specific risky conditions include:</p> <ul style="list-style-type: none"> use of untested or contaminated organic amendments. application of amendments with excessive heavy metals, pollutants or salinity. excessive nutrient loading, particularly nitrogen and phosphorus. use of immature compost causing phytotoxicity or nitrogen immobilisation; introduction of pathogens, weed seeds or invasive species. amendment application before erosion control and soil stabilisation. application on compacted soils without improving rooting conditions. assuming amendment use alone ensures safe food or feed production. lack of plant tissue testing and long-term monitoring of soil carbon and contaminants. 	<p>Monitoring should address both soil development and safety risks:</p> <ul style="list-style-type: none"> Biological/Chemical - soil organic carbon, total organic matter, C/N ratio, NPK availability, and cation exchange capacity. Enzymatic Activity Physical - bulk density, aggregate stability, infiltration rate, and water-holding capacity. Risk-related - total and bioavailable contaminants in soil, and contaminant concentrations in vegetation. 	<p>Good Practice: Characterized by the use of clean, tested inputs matched to the intended agricultural pathway, integrated with vegetation and fertility management.</p> <p>Conditional: When amendments improve functions but uncertainties remain regarding contaminant behaviour or long-term safety.</p> <p>Bad/risky Practice: Application of untested organic wastes, using amendments to mask unresolved failures (like compaction or contamination), or growing food crops without safety verification. Treating short-term "greening" as proof of long-term regeneration is also considered poor practice.</p> <p>In short, organic matter rebuilding is one of the most important biological reclamation practices for agricultural use of post-mining land. It helps transform a substrate into a functioning soil, but it must be managed as a controlled soil-building. Its success depends on amendment quality, appropriate dosing, integration with vegetation and fertility management.</p>

(Based on: Rodríguez-Berbel et al., 2025; Sae-Tun et al., 2024; Sheoran et al., 2010; Fernández-Caliani et al., 2021; Miu et al., 2022; Ducey et al., 2021; Mao et al., 2024; Li et al., 2021; Raghunathan et al., 2021).

Table 11. COFA Catalogue of soil regeneration and agricultural reclamation practices - fertility restoration and chemical correction

Reclamation/rehabilitation practice	Main purpose of the practice	Soil dysfunctions addressed	Examples of technical or biological measures	Suitability for agricultural reclamation pathways	Conditions under which the practice is recommended	Conditions under which the practice may be bad, insufficient or risky	Monitoring indicators needed to verify effectiveness	Relevance for good and bad practice assessment
fertility restoration and chemical correction	The primary goal of fertility restoration and chemical correction is to create chemical soil conditions that can support sustained plant growth and agricultural production on reclaimed post-mining land. This practice aims to correct nutrient deficiencies, unfavourable pH levels, and low sorption capacities that otherwise limit crop establishment and long-term soil development. The objective is not merely to apply fertilizers, but to specifically address the chemical limitations -such as extreme acidity or alkalinity - that prevent broader soil functions from developing. In an agricultural context, this ensures a more stable nutrient supply compared to simple revegetation, though it must be integrated with organic matter rebuilding and biological activation to be truly effective.	<p>Biological: addresses nutrient deficits to create conditions that stimulate microbial activity and root growth.</p> <p>Chemical: corrects deficiencies in essential nutrients (NPK, Mg, Ca, and micronutrients) and stabilizes critical parameters such as pH or CEC.</p> <p>Physical: indirectly supports soil structure by facilitating root-driven improvement.</p> <p>Hydrological: indirectly enhances water retention and improves the overall soil-water conditions.</p> <p>Contamination: manages food and feed safety by regulating pH to control contaminant uptake.</p>	<ul style="list-style-type: none"> Soil testing to diagnose nutrient deficiencies and pH imbalance before intervention. pH correction using lime, dolomite or other approved alkaline materials. Targeted mineral fertilisation based on soil and crop requirements. Supplementation of calcium, magnesium and micronutrients. Use of organic amendments, legumes, green manures and cover crops to improve nutrient supply and cycling. Integrated use of organic and mineral fertilisers to improve nutrient retention. Use of soil improvers that combine organic materials from composts or sewage sludge with mineral components like fly ash. Split fertiliser applications and monitoring of nutrient leaching to reduce losses. 	<p>Food Production: Requires the highest level of control, focusing on balanced nutrient supply, suitable pH, and low contaminant availability to ensure crop safety.</p> <p>Feed/ Grazing: Requires careful monitoring of nutrient balances and contaminants, as imbalances can affect forage quality and animal health.</p> <p>Industrial/ Energy Crops: These pathways may tolerate lower fertility than food crops, but chemical management is still required to maintain yield stability and prevent environmental degradation from repeated biomass harvesting.</p>	<p>This practice is recommended whenever soils reveal chemical constraints that limit plant growth, such as nutrient deficiencies or extreme pH levels. It is particularly critical in post-mining substrates that lack organic matter and have weak nutrient retention. It is particularly recommended when:</p> <ul style="list-style-type: none"> soil pH or exchangeable acidity limits plant growth, macro- or micronutrient deficiencies are diagnosed, cation exchange capacity or base saturation is unfavourable, crop or legume establishment is poor despite suitable physical conditions, organic matter contents is insufficient to sustain nutrient cycling, nutrient losses from biomass removal require compensation, soil amendments can safely improve fertility and chemical conditions. 	<p>This practice can be bad or risky when there is:</p> <ul style="list-style-type: none"> fertilisation or liming without prior soil testing and diagnosis, excessive nutrient application causing imbalances, leaching or runoff, use of sewage sludge, ash or industrial by-products without contaminant assessment, application of alkaline or saline amendments under unsuitable soil conditions, introduction of demanding crops before soil fertility and safety are verified, reliance on mineral fertilisers without rebuilding organic matter and biological activity, lack of monitoring of nutrient uptake, leaching and long-term soil response, treating fertilisation as a substitute for resolving physical, hydrological or contamination-related constraints. 	<p>To verify that chemical conditions are improving without creating new environmental risks, the following indicators should be monitored:</p> <ul style="list-style-type: none"> Chemical - soil pH, electrical conductivity (EC), exchangeable acidity, and cation exchange capacity (CEC), Nutrients - total and nitrogen, available phosphorus, potassium, magnesium, and calcium, Soil enzyme activity Plant tissue nutrient concentrations and crop yield or biomass production, Risk-related - total and bioavailable contaminants (especially if industrial amendments are used), nitrate leaching risk, and phosphorus runoff risk. 	<p>Good Practice: Diagnosis-based interventions, balanced nutrient supply, safe use of tested amendments, and integration with organic matter rebuilding.</p> <p>Conditional: When chemical correction is necessary but must be combined with other interventions; or when using waste-derived amendments that require strict control.</p> <p>Bad/risky Practice: Routine application of lime or fertilizers without diagnosis, over-application leading to pollution, using contaminated materials.</p> <p>In short, fertility restoration and chemical correction are necessary for agricultural reclamation, but they must be understood as controlled chemical rehabilitation rather than simple fertilisation. Their success depends on diagnosis, balanced nutrient management, safe amendment selection, integration with organic and biological soil-building measures, and long-term monitoring of soil, plant and water quality.</p>

(Based on: Larney & Angers, 2012; Diacono & Montemurro, 2010; Fernández-Caliani et al., 2021; Otremba et al., 2020; Maiti, 2022; Goulding, 2016; Wang et al., 2021; Sheoran et al., 2010; Feng et al., 2019).

Table 12. COFA Catalogue of soil regeneration and agricultural reclamation practices - water management and retention improvement

Reclamation/rehabilitation practice	Main purpose of the practice	Soil dysfunctions addressed	Examples of technical or biological measures	Suitability for agricultural reclamation pathways	Conditions under which the practice is recommended	Conditions under which the practice may be bad, insufficient or risky	Monitoring indicators needed to verify effectiveness	Relevance for good and bad practice assessment
water management and retention improvement	The main purpose of water management and retention improvement is to restore a functional soil-water regime in post-mining landscapes. This practice ensures that reclaimed soils can effectively receive, store, transmit, and supply water to plants to support vegetation establishment and long-term agricultural use. The objective is not merely to remove excess water or provide irrigation, but to rebuild the hydrological functioning of the reclaimed soil-landscape system. This includes improving infiltration, increasing water-holding capacity, and preventing both drought stress and waterlogging - conditions that often coexist on the same site due to disturbed drainage and compaction.	<p>Hydrological: Directly addresses low infiltration, poor water retention, excessive runoff, waterlogging, drought stress, and disrupted landscape drainage.</p> <p>Physical: Addresses issues related to compaction, poor soil structure, surface sealing, and unfavourable texture, all of which restrict how water moves through and is stored in the soil profile.</p> <p>Chemical/Biological: Indirectly addresses salinity, redox instability, and nutrient losses caused by poor drainage, as well as limited microbial activity and organic matter decomposition resulting from poor water retention.</p>	<ul style="list-style-type: none"> Assessment of site hydrology before agricultural use. Decompaction and suitable soil reconstruction to improve infiltration and water storage. Establishment of stable drainage systems, swales and retention structures where needed. Contour cultivation, mulching and organic matter addition to reduce runoff and evaporation. Use of perennial vegetation and cover crops to improve soil structure and water cycling. Selection of crops adapted to local moisture conditions. Monitoring of drainage water quality where salinity or contamination risks exist. 	<p>Food Production: Requires the highest level of hydrological control; areas must have verified stable water availability and good drainage to ensure reliable yields and machinery access.</p> <p>Feed/ Grazing: Requires stable moisture conditions; grazing must be delayed or adjusted.</p> <p>Industrial/ Energy Crops: Suitable for areas with less-than-ideal water conditions; drought-tolerant or wet-tolerant annual and perennial biomass crops can help stabilize soil and improve organic matter in these environments.</p>	<p>This practice is recommended wherever post-mining soils show disrupted moisture conditions that limit crop choice or machinery access. Specific recommended conditions include:</p> <ul style="list-style-type: none"> when infiltration is low due to compaction or surface sealing, where runoff and erosion occur frequently after rainfall. when reconstructed soils have low water-holding capacity (e.g., sandy or coarse substrates), where depressions cause persistent ponding or waterlogging, when drainage water is suspected of transporting salts or contaminants, before any land is assigned to intensive food or feed production. 	<p>Specific risky conditions include:</p> <ul style="list-style-type: none"> drainage installation without water-quality assessment, irrigation on saline or contaminated waters without monitoring, retention of contaminated runoff without treatment, creation of waterlogged zones in agricultural fields, uncontrolled runoff discharge onto unstable slopes, failure to maintain drainage channels or retention structures, use of heavy machinery on wet reclaimed soils, ignoring seasonal variation in water availability. 	<p>Monitoring should be seasonal and event-based to capture problems during drought or heavy rainfall. Indicators include:</p> <ul style="list-style-type: none"> Hydrological/Physical - infiltration rate, hydraulic conductivity, water-holding capacity, soil moisture by depth. Chemical - pH and EC of soil and drainage water, and nutrient concentrations in runoff. Agricultural - root depth and distribution, crop yield. 	<p>Good Practice: Hydrological diagnosis-based approach that integrates terrain shaping, soil reconstruction, and organic matter rebuilding to create a good water regime.</p> <p>Conditional: When water limitations are reduced but not fully removed; success depends on adapting the land-use pathway to remaining constraints (e.g., using drought-tolerant energy crops).</p> <p>Bad/risky Practice: Applying measures without diagnosis, uncontrolled drainage.</p> <p>In short, water management and retention improvement are essential for agricultural reclamation because water controls root growth, nutrient cycling, soil biological activity, machinery access and yield stability.</p> <p>Successful practice rebuilds a functional soil-water system matched to the reclaimed soil profile, landform and intended agricultural use.</p>

(Based on: Kozłowski et al., 2023; Kolodziej et al., 2016; Singh et al., 2022; Stachowski et al., 2018; Kaczmarek & Glina, 2018; Eden et al., 2017; Abdallah et al., 2021; Feng et al., 2019).

Table 13. COFA Catalogue of soil regeneration and agricultural reclamation practices - salinity and sodicity management

Reclamation/rehabilitation practice	Main purpose of the practice	Soil dysfunctions addressed	Examples of technical or biological measures	Suitability for agricultural reclamation pathways	Conditions under which the practice is recommended	Conditions under which the practice may be bad, insufficient or risky	Monitoring indicators needed to verify effectiveness	Relevance for good and bad practice assessment
salinity and sodicity management	<p>The primary goal of salinity management is to reduce the negative effects of excessive soluble salts (like sodium and sulphates) on soil structure, water movement, and plant growth.</p> <p>This practice aims to create a rooting environment where crops can germinate and function without osmotic stress, ion toxicity, or structural collapse.</p> <p>Effective management requires a site-specific diagnosis of the salt problem to combine hydrological, chemical, physical, and biological measures. In sodic soils specifically, the objective is to replace exchangeable sodium with calcium to restore soil hydraulic conductivity and aeration.</p>	<p>Chemical: Directly targets osmotic stress (which causes physiological drought), specific ion toxicity, nutrient imbalances, and poor germination rates.</p> <p>Hydrological/ Physical: Specifically addresses sodicity-driven dysfunctions such as clay dispersion, structural degradation, surface sealing, low infiltration, and waterlogging.</p> <p>Biological: Addresses the suppression of microbial activity, reduced organic matter decomposition, and limited soil fauna recovery caused by high salt concentrations.</p> <p>Contamination: In sulphur-rich post-mining areas, it is linked to managing high electrical conductivity and sulphate-related risks in drainage water.</p>	<ul style="list-style-type: none"> Diagnosis of salinity using EC, exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR). Identification of salt sources and assessment of drainage, permeability and soil texture. Improvement of drainage and controlled leaching of soluble salts. Application of gypsum or other calcium amendments where sodicity is confirmed. Avoidance of saline irrigation water and prevention of salt accumulation through proper surface grading. Use of salt-tolerant vegetation, mulching and organic amendments to improve soil structure and reduce evaporation. Decompaction or subsoiling where dense layers restrict leaching. Monitoring of soil and drainage water salinity before agricultural use. 	<p>Food/ Feed Production: Highly relevant but critical; these uses should be delayed or avoided until soil and plant testing confirm that salinity, associated contaminants are at safe levels.</p> <p>Grazing: Requires extreme caution as grazing on saline soils can damage vegetation and cause severe compaction; stocking density must be strictly controlled.</p> <p>Industrial/ Energy Crops: Often more suitable during transitional stages, provided that salt-tolerant species are used and biomass quality is monitored (especially if ash is returned to the land).</p>	<p>This practice is recommended whenever testing shows elevated EC, SAR, or ESP, or when visible field symptoms appear, specifically:</p> <ul style="list-style-type: none"> when surface crusting, sealing, or salt efflorescence is visible, where infiltration is low despite a suitable soil texture, where crops show characteristic salinity stress or poor germination, when saline overburden or sulphate-rich drainage from mining influences the rooting zone. 	<ul style="list-style-type: none"> Leaching salts is ineffective and potentially damaging if drainage is inadequate, as it may simply move salts within the profile or cause waterlogging, Gypsum application is insufficient if the soil is not actually sodic or if sodium-rich water continues to enter the system, Applying gypsum without diagnosis can temporarily increase salinity, Excessive leaching can mobilize contaminants or acidity into groundwater, Using saline organic amendments or poor-quality irrigation water can worsen the condition, Underestimating the seasonal changes. 	<p>Monitoring should be seasonal and capture vertical salt movement:</p> <ul style="list-style-type: none"> Chemical - EC (by depth), SAR, ESP, soluble sodium/ calcium/ magnesium, and chloride/sulphate concentrations, Hydrological/Physical - infiltration rate, saturated hydraulic conductivity, aggregate stability, surface crusting, and groundwater depth, Risk-related - crop emergence, visual stress symptoms, plant tissue sodium/chloride levels; EC and chemistry of drainage and irrigation water. 	<p>Good Practice Diagnosis-based intervention that distinguishes between salinity and sodicity, provides adequate drainage, uses amendment doses based on calculated requirements, and matches crop choice to current soil conditions.</p> <p>Bad/Risky Practice: Leaching without drainage control, applying gypsum without diagnosis, using saline amendments/irrigation, or treating "greening" as proof of unrestricted agricultural suitability.</p> <p>In short, salinity and sodicity management is a specialised but important component of agricultural reclamation where post-mining substrates, mine waters or amendments create salt-related constraints. Its success depends on correct diagnosis, water management, appropriate amendments, crop selection and long-term monitoring of soil, plant and water quality.</p>

(Based on: Shaygan & Baumgartl, 2022; Stavi et al., 2021; Bello et al., 2021; Paz et al., 2023; Leogrande & Vitti, 2019; Zaman et al., 2018; Shahid et al., 2018).

Table 14. COFA Catalogue of soil regeneration and agricultural reclamation practices - remediation and contaminant-risk reduction

Reclamation/rehabilitation practice	Main purpose of the practice	Soil dysfunctions addressed	Examples of technical or biological measures	Suitability for agricultural reclamation pathways	Conditions under which the practice is recommended	Conditions under which the practice may be bad, insufficient or risky	Monitoring indicators needed to verify effectiveness	Relevance for good and bad practice assessment
remediation and contaminant-risk reduction	<p>The primary goal of remediation and contaminant-risk reduction is to reduce unacceptable risks posed by contaminants in post-mining soils, waters, plants, and dust. This practice aims to prevent harmful exposure pathways, specifically the transfer of contaminants to crops, forage, livestock, and humans.</p> <p>Because complete removal of contaminants is often technically or economically unrealistic, the objective is to decrease mobility and bioavailability to a level compatible with the intended agricultural use.</p> <p>Remediation ensures that agricultural reclamation does not create direct food-chain exposure risks, which are a major concern when transitioning from mining land to food or feed production.</p>	<p>Contaminants: Elevated concentrations of toxic elements (e.g., Cd, Pb, Zn, As, Hg), acid-generating materials, and sulphate-rich or saline substrates.</p> <p>Chemical: Low pH, which often increases metal solubility and phytotoxicity, and unstable redox conditions that influence contaminant mobility.</p> <p>Biological: Inhibition of microbial activity, soil fauna, and root growth caused by toxicity.</p>	<ul style="list-style-type: none"> Detailed site investigation, contaminant mapping and separation of contaminated zones from agricultural areas. Removal, isolation or capping of highly contaminated materials where necessary pH correction and contaminant immobilisation using alkaline, mineral or organic amendments. Phytoremediation - phytostabilization using tolerant vegetation and plants that retain contaminants mainly in roots. Phytoremediation - controlled phytoextraction only where safe biomass disposal is possible. Erosion, runoff and dust control to prevent contaminant transport. Treatment and monitoring of contaminated drainage water, soil and vegetation. Exclusion of food and feed production from areas with unresolved contamination risks. 	<p>Food Production: Most restrictive; should only be considered where total and bioavailable contaminants meet strict legal safety requirements and crop safety is verified.</p> <p>Feed /Grazing: Requires strict control as contaminants can enter livestock via forage or direct soil ingestion; grazing should be avoided where surface contamination remains high.</p> <p>Industrial/ Energy Crops: More suitable as these are non-food pathways, but biomass quality must be controlled to prevent spreading contaminants through ash, dust, or processing residues.</p>	<p>This practice is recommended where contaminant concentrations or exposure pathways pose risks to human health, water or ecosystems, particularly when:</p> <ul style="list-style-type: none"> total or bioavailable contaminant concentrations exceed safety thresholds, low soil pH increases contaminant mobility, acid mine drainage or acid sulphate conditions are present, contaminated dust, sediment or drainage water can spread off-site, crops or vegetation accumulate contaminants contamination hotspots occur, food, feed or grazing use is planned without verified safety conditions. 	<ul style="list-style-type: none"> Relying on visual vegetation cover as proof of contaminant safety, Introducing food or feed crops without soil and plant testing, Applying amendments without contaminant-specific assessment, Mixing contaminated subsoil or waste materials into topsoil, Mobilising contaminants through inappropriate chemical conditions or poor water management, Use of contaminated amendments or industrial by-products, Inadequate management of contaminated biomass from phytoextraction, Allowing grazing where soil ingestion or contaminant uptake may occur, Failure to control contaminated dust or monitor long-term amendment stability and pH conditions. 	<p>Recommended monitoring indicators include:</p> <ul style="list-style-type: none"> laboratory toxicity tests (indicator species of plants, animals, and bacteria) soil microbial and biological activity where recovery is assessed. total and bioavailable contaminant concentrations in soil, soil pH, electrical conductivity and sulphate concentration where relevant, contaminant concentrations in crops, forage and phytostabilization vegetation, In-situ plant stress symptoms, contaminant concentrations in runoff, sediment, drainage water and groundwater, pH and conductivity of surface and drainage waters, organic matter, cation exchange capacity and amendment durability, 	<p>Good Practice: Risk-based, contaminant-specific remediation verified by soil, plant, and water monitoring, where land-use is strictly matched to safety levels.</p> <p>Conditional: When contaminants are stabilized but not removed; success depends on maintaining specific conditions like pH and erosion control.</p> <p>Bad/risky Practice: Redistributing contaminated materials; growing food/feed without testing uptake; or failing to monitor the long-term conditions.</p> <p>In short, remediation and contaminant-risk reduction are decisive for determining whether post-mining land can safely enter agricultural use. They do not always require complete contaminant removal, but they do require clear risk reduction, exposure-pathway control and monitoring. For agricultural reclamation, the key criterion is not only whether plants grow, but whether the intended agricultural products and management activities are safe over time.</p>

(Based on: Liu et al., 2018; Palansooriya et al., 2019; Hou et al., 2020; Mendez & Maier, 2008; Bolan et al., 2014; Song et al., 2022; Mai et al., 2024)

Table 15. COFA Catalogue of soil regeneration and agricultural reclamation practices - revegetation and crop establishment

Reclamation/rehabilitation practice	Main purpose of the practice	Soil dysfunctions addressed	Examples of technical or biological measures	Suitability for agricultural reclamation pathways	Conditions under which the practice is recommended	Conditions under which the practice may be bad, insufficient or risky	Monitoring indicators needed to verify effectiveness	Relevance for good and bad practice assessment
revegetation and crop establishment	<p>The primary goal of revegetation and crop establishment is to create a stable plant cover and initiate plant-driven soil development on reclaimed land. This practice protects the reconstructed soil surface from erosion and dust, improves organic matter inputs, and supports microbial and faunal activity.</p> <p>In agricultural reclamation, it serves as a functional step in rehabilitation - stabilizing the structure and preparing the land for production - rather than being mere proof that the land is already suitable for food or feed.</p> <p>It acts as a bridge between initial biological stabilization and productive land use.</p>	<p>Biological: Directly addresses low organic matter input, weak microbial activity, poor nutrient cycling, lack of soil cover, and limited soil fauna recovery.</p> <p>Physical: Root parts of plants stabilize soil, create biopores, reduce surface sealing, and provide critical protection against erosion on slopes and loose substrates.</p> <p>Hydrological: Plant cover improves infiltration, reduces runoff velocity, and increases surface roughness.</p> <p>Chemical: Supports recovery through nutrient uptake, litter return, and nitrogen fixation by legumes.</p>	<ul style="list-style-type: none"> ▪ Rapid establishment of protective vegetation following technical reclamation. ▪ In the case of difficult terrain introducing native pioneer herbaceous and grass plant species that can spontaneously colonise degraded areas in order to reduce erosion and initiate the soil regeneration process ➢ Use of grass-legume mixtures for rapid cover and nitrogen input. ▪ Sowing of perennial species on slopes and field margins. ➢ Use of cover crops and green manures during transitional stages. ➢ Planting deep-rooting species to improve soil structure and rooting depth. ➢ Selection of salt-, drought-, or metal-tolerant species where site-specific constraints exist. ➢ Phased introduction of productive crops (e.g., cereals, oilseed rape, maize). ➢ Use of perennial energy crops or short-rotation coppice on marginal land. ➢ Mulching or hydroseeding in high-erosion areas. ➢ Inoculation with rhizobia (for legumes) or mycorrhizal fungi. ➢ Strict control of weeds and invasive species. 	<p>Food Production: Requires the strictest verification of rooting depth, fertility, and safety; crops should only be introduced once monitoring confirms the soil is suitable for the human food chain.</p> <p>Feed /Grazing: Caution is required as contaminants can enter livestock via forage or soil ingestion; grazing must be delayed until vegetation is dense and soil structure is stable.</p> <p>Industrial and Energy Crops: Highly suitable as transitional soil-building systems; perennial biomass crops provide continuous cover and deep rooting on reclaimed soils.</p> <p>Staged Approach: COFA Recommendation is a sequence: protective cover → soil-building crops → non-food biomass → food crops.</p>	<p>This practice is recommended as soon as technical reclamation creates a stable surface that allows for plants germination.</p> <ul style="list-style-type: none"> • It is particularly critical when: • Bare reconstructed soil is exposed to erosion or dust. • Topsoil or amendments require immediate protection from wash-off. ▪ Biological activity is weak and nitrogen inputs are required through grass-legumes vegetation . • Long-term soil development for food crops land use requires continuous plant cover. 	<ul style="list-style-type: none"> • Insufficient if treated as a "cosmetic" final goal rather than a step; green surface may hide unresolved deeper issues like compaction or salinity. • Risky when introducing food/feed crops before safety testing; allowing grazing on weakly rooted or wet soils; using plants that accumulate contaminants in edible parts; or neglecting invasive species control. 	<ul style="list-style-type: none"> • vegetation cover percentage, • germination rate, • species composition, • aboveground and root biomass, • root penetration depth, • soil organic carbon, nutrient status, • contaminant concentrations in plant tissues and forage quality, • persistence of sown species and presence of weeds or invasive plants. 	<p>Good Practice: Species are selected based on site diagnosis, support organic matter accumulation, and match the intended agricultural pathway, with food/feed use only introduced after safety verification.</p> <p>Conditional: Vegetation stabilizes the site but land is used only for transitional pathways (e.g., energy crops) while soil continues to develop.</p> <p>Bad/risky Practice: Using vegetation as a cosmetic measure to mask unresolved dysfunctions, applying standard seed mixtures without diagnosis, or entering the food chain without safety testing.</p> <p>In short, revegetation and crop establishment are essential for transforming reconstructed post-mining substrates into functioning agricultural soils. However, their role is not only to make the land green. They must stabilise the surface, drive soil development, support biological activity and create a safe transition toward the intended agricultural use.</p>

(Based on: Buta et al., 2019; Maiti, 2022; Sheoran et al., 2010; Maiti, 2019; Feng et al., 2019; Kumar et al., 2015; Martin-Moreno et al., 2016).

Table 16. COFA Catalogue of soil regeneration and agricultural reclamation practices - regenerative agricultural management after reclamation

Reclamation/rehabilitation practice	Main purpose of the practice	Soil dysfunctions addressed	Examples of technical or biological measures	Suitability for agricultural reclamation pathways	Conditions under which the practice is recommended	Conditions under which the practice may be bad, insufficient or risky	Monitoring indicators needed to verify effectiveness	Relevance for good and bad practice assessment
regenerative agricultural management (after reclamation)	<p>The main purpose of regenerative agricultural management is to maintain and further improve soil functions after the formal reclamation phase is complete. Its primary objective is to prevent renewed degradation - such as erosion or re-compaction - while continuing the long-term process of rebuilding soil organic matter, physical structure, biological activity, and resilience. Since reclaimed soils remain young and vulnerable, this practice shifts the focus from one-time interventions to a continuous management system designed to support ongoing soil development under productive agricultural use.</p>	<p>This practice addresses dysfunctions that often persist or reappear after reclamation.</p> <p>Physical: Susceptibility to re-compaction, surface sealing, erosion risk, and weak soil aggregation.</p> <p>Hydrological: Poor infiltration and low water-holding capacity.</p> <p>Chemical: Long-term nutrient depletion and dependence on high external fertilizer inputs.</p>	<ul style="list-style-type: none"> ➢ Diversified crop rotations including legumes to support nitrogen cycling. ➢ Use of cover crops and maintaining living roots in the soil year-round. ➢ Reduced or minimum tillage to protect developing soil structure. ➢ Residue retention and incorporation of crop residues. ➢ Controlled traffic farming and the use of low-ground-pressure machinery to prevent re-compaction. ➢ Implementation of permanent grass strips, buffer strips, or contour cultivation. ➢ Integrated nutrient and pest management based on frequent soil testing. ➢ Rotational grazing with strictly controlled stocking densities. 	<p>Food/Feed Production: Highly suitable - requires a focus on building SOC and avoiding re-compaction; crop quality must be continuously monitored for safety.</p> <p>Industrial /Energy Crops: Fit well as transitional systems, providing continuous soil cover and high root biomass, however nutrient removal must be balanced.</p>	<p>This practice is recommended once basic technical and biological reclamation objectives have been met and the land is entering productive use.</p> <p>Particularly when:</p> <ul style="list-style-type: none"> • reclaimed soils remain vulnerable to erosion or compaction, • organic matter recovery is slow or biological activity remains low. 	<ul style="list-style-type: none"> • Applying regenerative practices without prior soil assessment or measurable targets, • Removing biomass without restoring nutrient and carbon losses, • Assuming improved vegetation cover guarantees food or feed safety, • Lack of long-term monitoring of soil health and contamination risks. 	<p>Long-term monitoring should include:</p> <ul style="list-style-type: none"> • assessing crop health using remote sensing methods (e.g. NDVI) • crop rotation diversity and crop cover • residue return rates and organic matter inputs, • crop biomass yield and forage quality, • contaminant concentrations in harvested biomass and agricultural products. 	<p>Good Practice: Maintaining continuous soil cover, reducing disturbance, and using an outcome-based approach verified by long-term soil-health monitoring.</p> <p>Bad/risky Practice: Using the term "regenerative" to mask unresolved reclamation failures.</p> <p>In short, regenerative agricultural management is the post-reclamation phase that determines whether reclaimed land continues to develop as a functioning agricultural soil or gradually degrades again. It should be treated as long-term soil management based on diagnosis, adaptive management and monitoring, not as a fixed package of practices or a substitute for remediation and reclamation requirements.</p>

(Based on: Jian et al., 2020; Khangura et al., 2023; Chamen, 2015; Prairie et al., 2023; Giller et al., 2021; Lal, 2020; Teague & Kreuter, 2020).

6. EXAPLES OF POST-MINING SOIL REHABILITATION PRACTICES IN POLAND

Agricultural reclamation in Poland's lignite regions, especially the Konin Basin, has been developed over several decades with detailed monitoring of soil, crops and water. Work by Gilewska, Otremba, Kasztelewicz and co-authors provides concrete yields, soil parameters and reclamation shares for Konin and other mines (Gilewska, 2018; Kasztelewicz, 2014; Kołodziej et al., 2016).

6.1. Scale and directions of reclamation

In Polish lignite mines, about 20% of reclaimed land goes to agriculture, ~60% to forestry and ~10% to hydrological uses (Kasztelewicz, 2014).

In Konin and Adamów, reclamation is relatively agriculture-oriented: 50-59% agricultural, 17-31% forestry, 8-24% hydrological (Kasztelewicz, 2014).

Konin mine has been a national leader; by 2012 about half of all reclaimed lignite-mine land in Poland was in Konin (Frydrychowicz, 2024).

Table 17. Percentage of Agricultural reclamation comparing all reclamation directions.

Mine	Agricultural	Forestry	Hydrological	Other (special + recreational)
Konin	50%	31%	8%	11%
Adamów	59%	17%	24%	1%

(Based on: Kasztelewicz, 2014)

6.2. Soil rehabilitation practices and outcomes at Konin Lignite Basin

Agricultural reclamation was for many years the leading reclamation direction implemented by the Konin mine. Its dominance resulted from the presence of grey glacial tills in the overburden, which, due to their properties, constitute an excellent material for both agricultural and forest reclamation.

The foundations of agricultural reclamation were developed by the creators of the Polish Academy of Sciences (PAN) model. The method they proposed requires the preparation of spoil material with specific properties. This can be achieved through selective dumping, whereby the upper layer of the spoil heap consists mainly of grey tills, allowing for adequate productivity of newly formed soils. Achieving the desired outcome, however, requires numerous technical and technological operations, as well as a series of agrotechnical treatments. Increased amounts of mineral fertilizers are applied to the prepared substrate, followed by sowing a seed mixture of alfalfa (*Medicago sativa* L.) and appropriately selected grass species.

As a result of these measures, a soil layer suitable for the establishment of agricultural fields is created. Such areas were developed on post-mining lands of the Gosławice, Józwin, Kazimierz, Państwów, and Lubstów open pits. Crops cultivated on reclaimed post-mining land include wheat, sugar beet, rapeseed, sunflower, and maize. Research indicates that agricultural production on reclaimed land is often more efficient than on the native sandy soils characteristic of the Konin region (<https://kwbkonin.pl/>).

Bender's PAN model / target species concept guides Konin's agricultural reclamation by matching reclamation treatments and plant species to soil material and intended land use (Gilewska, 2018; Kaczmarek et al., 2023; Otremba et al., 2020).

Repair of soil chemism (pH and nutrient balance) through NPK fertilization is described as the most important reclamation treatment (Gilewska, 2018; Kaczmarek et al., 2023; Otremba et al., 2020).

Long-term alfalfa and orchard grass monocultures with 0, 1 or 2 NPK doses (e.g. 160–320 kg N ha⁻¹ yr⁻¹) significantly increased SOC, total N, P₂O₅, K₂O and cation exchange capacity (CEC), often reaching levels higher than average Polish arable soils (Otremba et al., 2020).

Physical studies at Pątnów showed reclaimed technogenic soils (sandy loam and loamy sand) characterized by high macroporosity and good plant-available water. Spontaneous succession produced the most favourable overall physical state, although all tested agricultural variants, including black fallow, provided adequate air–water relations (Kołodziej et al., 2016).

Gilewska (2018) presented example crop yields on reclaimed Konin soils from 40-year study:

- Winter rape, no NPK: ~0-0.4 dt/ha
- Winter rape, 1 NPK: average 12.7 dt/ha
- Winter rape, 2 NPK: average 14.9 dt/ha
- Winter wheat, no NPK: average 8.1 dt/ha
- Winter wheat, 1 NPK: average 34.2 dt/ha
- Winter wheat, 2 NPK: average 38.3 dt/ha (Gilewska, 2018).

These numbers demonstrate that agricultural use without fertilization is practically impossible, whereas appropriate NPK fertilization increases yields to an economically viable level (Gilewska, 2018; Otremba et al., 2020).

6.3. Examples of good and poor outcomes of rehabilitation in Poland

6.3.1. Good / promising outcomes

Long-term agricultural reclamation at Konin has produced chemically rich Technosols characterized by high SOC, nitrogen content and cation exchange capacity (CEC), together with sustained alfalfa yields ranging from 15 to 60 t/ha/year depending on fertilization level (Otremba et al., 2020).

Spontaneous succession and vegetated reclamation variants improve soil structure and organic carbon accumulation, resulting in better physical soil quality than unvegetated black fallow systems (Kołodziej et al., 2016).

In some Polish mining areas, including Konin and Adamów, the post-reclamation soil quality class has been reported as equal to or even better than the pre-mining condition on parts of the reclaimed land (Kasztelewicz, 2014).

6.3.2. Problems and limitations

Reclamation outcomes depend strongly on both parent material and long-term management practices. Without corrective fertilization or vegetation cover, productivity remains extremely low, including near-zero winter rape yields in unfertilized variants (Gilewska, 2018; Kołodziej et al., 2016; Otremba et al., 2020).

A case study from the Zn-Pb Trzebionka mine illustrates a “bad practice” example: a 25 cm inert soil cover placed over toxic tailings did not sufficiently isolate Zn, Pb and Cd contamination, and elevated

mobile metal concentrations in subsoil continued to pose risks of plant uptake (Tarnawczyk et al., 2021).

Hydrological changes and long-term subsidence may also degrade vegetation cover decades after reclamation. Such processes have been identified using remote-sensing vegetation indices in reclaimed mining landscapes (Buczyńska et al., 2020; Buczyńska et al., 2023).

6.4. Broader Polish context and multifunctionality

In Poland, reclamation is increasingly understood not only as “greening” degraded land, but as the creation of multifunctional post-mining landscapes integrating agriculture, forestry, recreation and water management within sustainable development frameworks (Galiniak, 2012; Kasztelewicz, 2014; Pietrzykowski et al., 2018).

In the Adamów mining area, hydrological reclamation has been used to create seven large reservoirs, increasing water retention capacity and supporting irrigation of adjacent agricultural land (Stachowski et al., 2018).

Early-successional meadows, legumes and young forests in the Adamów post-mining landscape may also provide high pollination-service potential beneficial for beekeeping and surrounding agriculture (Łowicki et al., 2021).

Studies of Konin post-mining soils additionally indicate the presence of bacterial and fungal communities with traits favourable for plant growth and bioremediation, highlighting the importance of soil microbiota in long-term restoration success (Lewandowska et al., 2026).

Polish experience, especially in the Konin Lignite Basin, shows that successful agricultural reclamation of post-mining land requires active soil chemical repair (particularly NPK fertilization), careful choice of target plant species, and sustained vegetative cover. Where these measures are applied, reclaimed technosols can reach or even surpass typical arable soil quality and support commercially relevant crop and fodder yields. However, thin or poorly designed covers over contaminated substrates, or omission of fertilization and vegetation, lead to very low productivity or persisting contamination risks. Modern practice increasingly integrates agriculture with forestry, water reservoirs, biodiversity (pollinators, microbes) and recreation to build multifunctional post-mining landscapes.



Figure 9. Agricultural reclamation of the summit area of the external spoil heap of the Lubstów open-pit mine.
Source: [KWB Konin](#)



Figure 10. Maize and sunflowers cultivated on the internal spoil heap of the Józwin open-pit mine.
Source: [KWB Konin](#)



Figure 11. Sugar beet cultivation on the internal spoil heap of the Józwin open-pit mine.
Source: KWB Konin

6.5. Unique features of Sieniawa's agricultural reclamation

Sieniawa Lignite Mine is frequently presented as an example of sustainable deposit management and good reclamation practice in Polish lignite mining. Unlike many large open-pit operations where reclamation is largely conducted after the completion of mining activities, reclamation in Sieniawa is closely integrated with ongoing extraction. This progressive approach reduces the extent of long-term degraded land and enables the rapid return of reclaimed areas to productive use (Galiniak, 2012; Kasztelewicz, 2014).

The mine operates within relatively complex geological conditions characterized by glacially disturbed lignite deposits, heterogeneous overburden materials and highly variable soil conditions. Despite these challenges, reclamation activities have been systematically implemented throughout the life of the mine, resulting in the restoration of most post-mining areas to agricultural, forestry and water-management functions.

6.5.1. Integrated, multi-use landscape approach

A distinguishing feature of reclamation in Sieniawa is the deliberate creation of a multifunctional post-mining landscape. Rather than focusing on a single reclamation objective, reclaimed areas are developed simultaneously for agricultural production, forestry and aquatic ecosystem functions.

This approach reflects modern ecosystem-oriented reclamation principles, where post-mining land is transformed into a diverse landscape mosaic capable of delivering environmental, economic and social benefits. Agricultural fields, forest plantations, wetlands and small water bodies are integrated into a coherent landscape structure, enhancing biodiversity, landscape attractiveness and ecosystem resilience (Galiniak, 2012; Pietrzykowski et al., 2018).

Particular attention is given to maintaining ecological connectivity. Afforestation has been implemented in areas adjacent to existing forests, while terrain depressions containing water have been incorporated into reclamation designs as habitats supporting local flora and fauna. Such measures demonstrate that agricultural reclamation can be successfully combined with broader ecological restoration objectives.

6.5.2. Agricultural soil rehabilitation specifics

Agricultural reclamation in Sieniawa is based on a comprehensive soil rehabilitation strategy that combines technical landforming, selective material management and biological soil improvement.

One of the most important good practices is the preservation and reuse of biologically active topsoil. Prior to mining operations, humus-rich topsoil is removed and stored separately. During reclamation, this material is reapplied to reconstructed land surfaces, supporting the rapid restoration of soil biological activity, nutrient cycling and agricultural productivity. The geological characteristics of the overburden provide favourable conditions for agricultural reclamation. A significant proportion of the overburden consists of silty materials considered potentially productive for future agricultural use. Following appropriate fertilization and soil improvement measures, these materials are capable of supporting the development of functional agricultural soils.

A particularly important reclamation practice involves the selective management of potentially problematic materials. Carbonaceous sediments and sulphur-bearing strata associated with the lignite seam are placed in deeper parts of the excavation and isolated from surface layers using more suitable materials such as sands and glacial tills. This minimizes the risk of soil acidification and reduces the likelihood of long-term soil quality degradation.

After technical landforming, reclaimed surfaces undergo detailed quality control. Any acid-forming materials exposed at the surface are neutralized through liming, while soil fertility is further improved through fertilization and agrotechnical treatments. Agricultural areas are subsequently sown with leguminous pre-crops and other vegetation capable of accelerating biological soil development, increasing organic matter inputs and improving soil structure.

The mine also applies erosion-control measures through appropriate slope design. Agricultural slopes are generally formed at gentle gradients that reduce surface runoff and limit soil loss. Former access roads are reconstructed to ensure continued agricultural accessibility and long-term land usability.

As a result of these practices, reclaimed areas have been successfully returned to agricultural production. The reclaimed soils support crops such as maize, lucerne and pasture vegetation, demonstrating the effectiveness of the soil rehabilitation process.

6.5.3. Why Sieniawa is considered unique

Sieniawa is widely regarded as one of the most successful examples of progressive agricultural reclamation in Poland. Several factors contribute to this status.

First, reclamation is conducted continuously alongside mining operations rather than being postponed until mine closure. This substantially reduces the area of disturbed land at any given time and shortens the period during which land remains unavailable for productive use.

Second, reclamation in Sieniawa is based on careful management of soil and overburden resources. The preservation of topsoil, selective placement of potentially harmful materials, systematic liming and biological improvement measures represent a comprehensive soil rehabilitation strategy rarely documented in such detail.

Third, reclamation objectives extend beyond simple restoration of pre-mining land conditions. In some locations, terrain reshaping, slope stabilization and the application of substantial humus layers have reportedly increased the utility value of the restored land compared with pre-mining conditions. This demonstrates an approach focused on land improvement rather than merely repairing mining-related disturbance.

Finally, Sieniawa illustrates how a relatively small lignite operation can successfully implement ecosystem-based reclamation principles comparable to those applied in larger mining regions. The case demonstrates that agricultural reclamation can be integrated with forestry and ecological restoration while maintaining productive land use and supporting local communities.

Overall, the Sieniawa case represents a strong example of good practice in agricultural reclamation and soil rehabilitation. Through progressive reclamation, careful soil management, selective handling of overburden materials and integration of ecological and agricultural objectives, the mine demonstrates how post-mining landscapes can be transformed into stable, productive and environmentally functional systems.



Figures 12-13. Mining area in August 2020 with active mining operations (top). The same post-mining area in November 2022 reclaimed in agricultural direction (bottom). Source: [KWB SIENIAWA](#)

6.6. Differences in reclamation and soil rehabilitation approaches between hard coal and lignite post mining areas

Agricultural reclamation of hard coal post-mining areas involves different challenges than those associated with opencast lignite mining. The main consequences of underground hard coal mining are the creation of waste rock dumps and ground subsidence, which most often result in the formation of areas with increased waterlogging or that are periodically or permanently flooded. In the case of areas where degradation results in increased soil moisture, one might also consider growing energy crops that are highly resistant to periodic flooding, such as energy willow. High water demand and transpiration rates may also contribute to improved water conditions in such degraded areas. A much greater challenge is the use of agricultural reclamation for carboniferous rock waste disposal sites.

Waste rock dumps are usually much smaller than those formed at open-pit mines and often are shaped with steep slopes, which limits their use for agricultural purposes. The detailed analyses in [REECOL Project](#) indicate that the main cause of limited vegetation growth on waste rock dumps is the limited availability of phosphorus and, probably, nitrogen, as well as the low content of easily decomposable organic matter. Another degrading factor is often the improper physical structure of the substrate. Content of skeleton particles 2mm is above 60% and it is much higher than in agricultural native soil. This could have negatively impact on the substrate water holding capacity. This soil structure makes it impossible to perform agricultural operations such as ploughing. Waste from hard coal mining has a dark colour, which causes the unvegetated surface of the spoil heap to heat up significantly during periods of intense sunlight. As a result, vegetation is exposed to severe thermal even in the early stages of development (as early as April and May). High surface temperatures also cause water deficits in plants, especially during periods of heat and drought. Despite these factors that limit plant growth, it appears feasible to reclaim these areas for agricultural use, particularly for the cultivation of energy crops. This is evidenced by the successful reclamation of carboniferous rock dumps for forestry purposes. One positive aspect is that waste dumps from hard coal mining in the Upper Silesia region characterized by low levels of trace substances (e.g. heavy metals) that could pose an environmental and health risk.

7. EXAPLES OF POST-MINING SOIL REHABILITATION PRACTICES IN CZECHIA

The diagram illustrates the technology of agricultural reclamation used in the Czech Republic after surface mining (especially in the Most Basin). The entire procedure complies with Czech legislation (Mining Act No. 44/1988 Coll., Agricultural Land Fund Act No. 334/1992 Coll.) and methodologies applied since the 1960s in the North Bohemian brown coal basin.

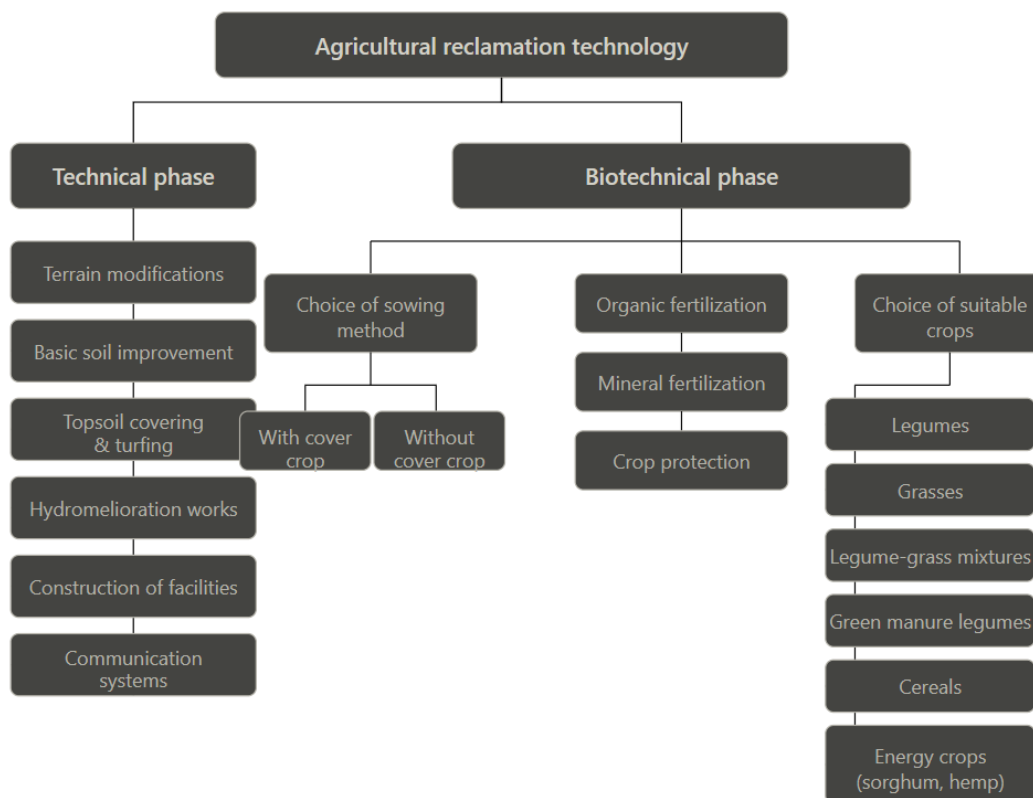


Figure 14. Technology of agricultural reclamations used in Czechia.
(Source: Kryl et al., 2002; Vrábliková & Vráblik, 2010).

As shown in the Figure 14, reclamation workflow is divided into two main phases. The Technical Phase covers terrain preparation, soil improvement, topsoil placement, hydro-melioration, and infrastructure construction. The Biotechnical Phase encompasses the choice of sowing method, fertilisation strategy, crop protection, and the selection of suitable reclamation crops.

7.1. Reclamation-relevant fertile soils and amelioration materials used in modifying spoil heap soil properties

The choice of soil-forming substrate is the foundation of the Biotechnical Phase (Figure 14). These fertilizing soils are alternatives that can be used.

- Humus horizons (topsoil) - These are the most valuable, selectively salvaged soil-forming substrates, which should be used primarily for agricultural purposes during reclamation. They are characterized by high water retention, higher porosity, and good soil structure.
- Loess loam - These are other significant soil-forming substrates of Quaternary origin. In loess, the carbonate content can exceed 5 %, while in loessy clays it usually remains below 3 %. In the Most Basin area, loessy clays are characterized by a higher content of physical

clay and represent the most important group of fertile soils here, primarily used for forestry purposes. These soils are mostly structureless, characterized by high water retention and relatively low porosity.

- Marlite - This is a rock suitable especially for the improvement of anti-erosion properties of texturally heterogeneous spoil soils (see COFA 3.1 Report). Clays and claystones have, compared for example to loess soils, less favourable soil properties, which is primarily due to a higher content of calcite and the presence of unweathered rock and skeleton. Weathered claystones are characterized by medium to high water retention and rather low to moderate porosity.
- Bentonite - These are rocks of Tertiary age with wide application in reclamation, especially in the modification of the chemical, physical, and anti-erosion properties of soils. Significant deposits in the Most Basin are found in the Braňany area near Most and Rokle near Kadaň (see COFA 3.1 Report). These rocks are characterized by high water retention and considerable porosity. When mixed with other spoil soils, they also show good swelling ability, thereby positively influencing the resulting properties of the soil profile.
- Organic wastes, industrial composts - Waste of organic origin can, under certain conditions, become a significant source of humus in the soil, but it can also fulfil important anti-erosion functions and regulate the soil water regime (Čermák & Ondráček, 2006).

The specific combination and application depth of these materials depends on the reclamation method selected.

7.2. Technological processes of creating anthropogenic soil for agricultural purposes

Two principal methods are used for creating anthropogenic soil profiles, corresponding to the topsoil covering & turfing step in the Technical Phase (Figure 14). The method chosen determines the subsequent crop rotation duration described in Section 7.3 of this report.

- Direct reclamation - represents a biological modification of soils deposited on the surface of spoil heaps, which can originate from the Quaternary as well as the Tertiary period. Currently, this method of reclamation has only limited significance for agricultural use. Soils created in this way are mostly heavy in texture, exhibit less favourable physical and anti-erosion properties, and are difficult to work with. For this reason, direct reclamation is applied mainly in cases where the intention is permanent grassing of the area or the establishment of other purpose-driven greenery (Čermák & Ondráček, 2006).
- Indirect reclamation - consists of covering the technically modified surface of the spoil heap, most often with a layer of humus horizon (topsoil). The minimum thickness of this layer is usually less than 0.3 m, while the optimal thickness is around 0.5 m. In case of a shortage of topsoil, two-layer coverings can be used. First, a lower quality material with a thickness of approximately 0.2–0.3 m is spread over the spoil heap soils, which is then covered with a layer of topsoil of the same thickness. Before applying topsoil or other ameliorative soils, it is advisable to loosen the surface of the spoil heap to improve the hydro-physical connection between individual layers and the overall functionality of the soil profile. Indirect reclamation utilizing humus horizons is the most common method of creating anthropogenic soils in the Czech Republic. In the past, humic anthropogenic soils with a topsoil layer up to 0.3 m thick were often used. Currently, however, the highest quality variant of agricultural reclamation is considered to be deep-humic anthropogenic soil with a humus horizon thickness of around 0.5 m (Čermák & Ondráček, 2006).

7.3. Reclamation crop rotation practices

Once the anthropogenic soil profile has been established by direct or indirect reclamation, the Biotechnical Phase of Figure 14 is initiated through a preparatory agrocycle. The length of this cycle is directly linked to the soil profile depth achieved in the previous step.

Two reclamation agrocycle lengths lasting 2-3 years are recommended, during which mainly clovers and grasses are grown. These crops have lower nutrient and care requirements and are usually mown twice a year, with the resulting biomass also being usable for mulching. A two-year preparatory agrocycle is suitable for the creation of deep-humus anthropogenic soils (with a topsoil cover up to 0.5 m). A three-year cycle is recommended for humus-rich anthropogenic soils (with a topsoil layer up to 0.3 m) or for combined covers, where, in addition to topsoil, loess clay or marl is also used (Čermák & Ondráček, 2006).

7.4. Completion of biological reclamation

After the reclamation agrocycle described in Section 7.3, the resulting anthroposol undergoes formal evaluation before it is transferred to the agricultural soil fund. The evaluation criteria for anthroposols consist of assessing whether the soil profile corresponds to the project design and whether there are depressions on the area causing waterlogging or the formation of permanent water bodies. The basis of the evaluation is the determination of the evaluated soil-ecological unit, a national framework for assessment of agricultural land fund, which is preceded by a pedological survey focused on stratigraphy and basic soil properties. Based on this data and its comparison with the natural soils of the given area, the anthroposol is classified into the appropriate classification unit. These units are defined according to climate, soil properties, soil-forming substrates, slope, stoniness, and soil profile depth and are labelled with a five-digit numerical code (Čermák et Ondráček, 2006).

7.5. Use of agriculturally reclaimed anthropogenic soils after the end of the agrocycle

The classification unit assigned at the end of biological reclamation (Section 7.4) determines the range of viable post-reclamation land uses. The Choice of crops branch of Figure 14, legumes, grasses, legume-grass mixtures, cereals, and energy crops, reflects the options available across the full quality spectrum of reclaimed soils.

Soils considered suitable for intensive agricultural production are primarily those in which a sufficiently thick humus horizon was created during reclamation. With intensive management, these soils can reach a production capacity of up to around 80 % compared to natural soils, and their use can be considered promising in the long term. Reclaimed spoil heaps can also be used for growing fruit, industrial, or energy crops, especially on areas with a top layer of topsoil or in the direct reclamation of substrates from loess clays and Tertiary sands or clays with more favourable properties. However, this use often has an extensive character, mainly due to higher management costs and limited marketing opportunities for the production (Čermák et Ondráček, 2006).

7.6. Remediation of phytotoxic areas

Where standard indirect reclamation is not applicable, particularly when spoil heap surfaces consist of phytotoxic overburden, a specialised remediation procedure is required prior to entering the Biotechnical Phase (Figure 14).

Phytotoxic soils represent overburden materials of coal seam layers. They usually consist of a heterogeneous mixture of lighter-textured soils (sandy loam to sandy), containing admixtures of

burned clays and a high proportion of coal matter, limonitized sandstone, pyrite, and locally also siderite. In the conditions of the Most Basin, sites are considered phytotoxic especially when they contain high levels of coal (over 5 %), siderite, pyrite, marcasite, and sulphur (approximately 3-5 %) (Řehoř et al., 2006; Řehoř, 2007; Vráblíková et al. 2010).

Two basic approaches are used for the reclamation and remediation of these soils. Both options conclude with the same preparatory agrocycle and compost application parameters, which are described once below and apply equally to both variants.

- First option involves the application of marly or bentonitic soils, alternatively shale or local brown clays, in amounts of approximately 2,500-3,500 m³·ha⁻¹. This is followed by homogenization, most commonly by cross ploughing to a depth of 0.5–0.6 m. The reclaimed surface should have a maximum slope of 16 % (1:6). After its completion, autumn planting of forest tree seedlings can be carried out (Vráblíková et al. 2018).
- An alternative approach consists of covering the surface of the reclaimed area with a layer of loess loam up to 0.5 m thick, usually without the need for deep soil cultivation (ploughing). In this case, the slope of the reclaimed surface is not significantly restricted for sandy and phytotoxic soils. A suitable supplementary method may also include spot mulching around planted tree seedlings. After its completion, the establishment of forest stands can begin (Vráblíková et al. 2018).

Regardless of the option chosen, organic matter (compost) with an adjusted C:N ratio of approximately 25:1 is applied at a rate of around 200 t·ha⁻¹ and incorporated into the soil to a depth of 0.20–0.30 m. This is followed by a two-year preparatory agrocycle involving the cultivation of green manure crops, consistent with the agrocycle described in Section 4 for deep-humus anthropogenic soils (Řehoř et al., 2006; Řehoř, 2007; Vráblíková et al. 2018).

7.7. Case studies from the Most Basin

This section describes selected examples of successful and unsuccessful large-scale agricultural, reclamations in the Most Basin.

7.7.1. Radovesice spoil heap

The Radovesice spoil heap is the largest spoil heap of the Severočeské Mines company. The construction of the dump began in 1964, and the placement of overburden was completed in 2003. The site was originally dominated by sterile and hazardous sands. Silt clays were present to a lesser extent, with occasional occurrence of phytotoxic soils of the stratified layers (Řehoř, 2007; Frašita et al. 2014; Mach et al. 2022).

Marls and marlstone were applied, given the unsuitable pedological conditions, as a low-cost, available means to stabilise sandy spoil heaps. This approach to optimising soil properties is uncommon. Greater emphasis was therefore placed on developing the correct methodology for applying these substrates, with dosage adjusted over time based on long-term pedological monitoring. Technical reclamation is now practically completed. Reclamation work has been carried out in the whole area, except for two experimental succession areas (Figure 15). Agricultural reclamation at the site follows on from the reclamation of the older, adjacent Jirásek spoil heap (Řehoř, 2007; Frašita & Řehoř, 2014; Mach et al. 2022). If comparable post-mining areas exhibit similar soil dysfunctions in future, the application of marl and marlstone can be considered as an alternative but only following thorough pedological investigation and appropriate dosage determination.



Figure 15. Radovesice XVIIA (succession). Source: [VUHU](#)

7.7.2. Ležáky quarry - Lake Most

This project is an example of so-called hydric reclamation and forms part of a broader revitalization of approximately 1,300 hectares, which also includes forestry, agricultural, and other types of reclamation (DIAMO, n. d.).

An important feature of this area is the presence of successional sites (Figure 16), which develop through natural vegetation processes without significant human intervention, particularly on spoil heap slopes and in areas with problematic soil conditions (DIAMO, n. d.). These sites may locally be burdened by residues of mining activity, including potentially toxic substances, which limits conventional reclamation approaches and highlights the importance of natural succession as a stabilizing ecological process (Euroregion Krušnohoří, 2021).



Figure 16. Lake Most (succession). Source: [VUHU](#)

7.7.3. Střimice spoil heap

The Střimice spoil heap is located near the town of Most and was established between 1959 and 1973. The spoil heap is divided into two parts. The first, successional part covering 2 ha is the edge section of the Střimice spoil heap (Figure 4). The second part of the Střimice spoil heap is a recultivated area covering 10 ha (Řehoř, 2007).

The predominant soil type on the area is a heterogeneous mixture of overburden soils from the coal seams of the Bílina surface mine, such as sandy clay loams and sands with a distinct admixture of coal and siderite. These soils are extremely acidic and phytotoxic. Remarkable development of erosion gullies with depths of up to several metres is evident on the surface. The extremely acidic nature of the environment creates inhospitable conditions for vegetation. Vegetation is represented minimally, though rare acidity-tolerant species occasionally occur. In cases of contamination by coal material, ameliorative rocks are being utilised, specifically the marly rocks or bentonitic soils. Bentonites from the nearby Red Hill quarry were applied as part of reclamation of the phytotoxic area on the Střimice spoil heap (Řehoř, 2007; Luxa, 1997).

The results of the applied reclamation method showed a positive response to the selected technique of bentonite application. However, the market price of bentonitic rocks and the risk of contamination by certain hazardous elements present in these materials may pose obstacles. Greater attention must therefore be paid to soil pedological properties and present dysfunctions when selecting this measure in future (Řehoř, 2007).

Forestry reclamation dominates the reclaimed area, with agricultural reclamation represented to a lesser extent.



Figure 17 Střimice (succession, phytotoxic site). Source: [VUHU](#)

8. EXAPLES OF POST-MINING SOIL REHABILITATION PRACTICES IN GREECE

8.1. Agricultural reclamation and soil rehabilitation in Western Macedonia

Lignite was one of the main sources of electricity generation in Greece for many decades, until the growth of renewable energy and the implementation of decarbonization policies promoted a transition toward sustainability. The region of Western Macedonia served as the country's principal lignite mining area, hosting Greece's largest lignite-powered plants with a combined installed capacity of approximately 4,300 MW (Kondyla et al. 2025).

The development of the Lignite Centre of Western Macedonia occupied more than 17,000 hectares and generated annual excavations exceeding 170 million m³ (Pavloudakis et al., 2018). The mining operations in the Lignite Centre of Western Macedonia were employed in Ptolemais and Amyntaion. In parallel with the mining activities, extensive environmental reclamation work was underway. The reclaimed land has been utilized for various purposes, such as agriculture, forestry, recreational purposes and installation of RES. Currently, the only two active mines (Mavropigi and South Field) are in a closure phase and are expected to stop lignite production by the end of 2026, while reclamation works will continue until all required activities defined in the mine environmental permitting terms are completed (Pavloudakis et al. 2026).

Following the Greek lignite phase-out strategy introduced within the National Energy and Climate Plan, reclamation and post-mining land management have become increasingly important for the future development of the region. In Western Macedonia, reclamation approaches evolved from purely technical stabilization toward integrated ecological and agricultural rehabilitation strategies adapted to local climatic and soil conditions (Antoniadis et al., 2021).

8.1.1. Soil Degradation in post-mining areas

Mining activities in Western Macedonia resulted in numerous unavoidable landscape and land cover and use changes. The active mining area was continuously expanded, while reclamation work has been carried out over the last 45 years to reduce landscape degradation and other environmental impacts. An assessment of land cover and use changes in the Ptolemais mining area, from a spatiotemporal perspective, was employed in the study of Paraskevis et al. (2021), for the period between 1990 and 2018. The study found that the mining activities led to the creation of "green" land uses by establishing an extensive forestation and creation of agricultural areas programme, fulfilling the mining operator's commitment to sustainable mining.

The semi-continental Mediterranean climate of Western Macedonia further complicates reclamation processes due to long dry summers, irregular precipitation patterns and increasing drought frequency. These factors make soil rehabilitation and vegetation establishment particularly challenging and require integrated reclamation approaches combining technical stabilization with biological restoration (Pavloudakis et al., 2018).

8.1.2. Agricultural reclamation practices

Agricultural reclamation in Western Macedonia began during the 1980s through experimental cultivation projects implemented on reclaimed waste dump surfaces (PPC, 2009). These studies demonstrated that reclaimed mine soils could gradually regain productive capacity when appropriate soil rehabilitation measures were applied.

Experimental wheat cultivation produced yields comparable to surrounding agricultural areas, confirming the feasibility of long-term agricultural reuse of reclaimed mining land (Pavloudakis et al., 2011; Pavloudakis et al., 2019; Pavloudakis et al., 2020).

As reclamation strategies evolved, increasing attention was given to diversified and climate-resilient agricultural systems. Aromatic and medicinal plants were identified as particularly suitable for reclaimed areas due to their relatively low irrigation requirements and high economic value (Pavloudakis et al., 2018). According to Papadopoulou et al. (2015), reclaimed soils in Western Macedonia are characterized by relatively good quality, low heavy metal concentrations and adequate nutrient content, supporting their suitability for agricultural applications.

The agricultural reclamation program also included the establishment of orchards containing apple, pear, plum and cherry trees, together with vineyards intended to demonstrate the potential for higher-value agricultural production systems in reclaimed mining landscapes (Figure 18) (PPC, 2009).



Figure 18 The orchard in the area of the Main Field mine. Source: PPC.

8.1.3. Soil rehabilitation measures

Soil rehabilitation in Western Macedonia focused primarily on the physical and chemical functionality of mine substrates. Technical shaping of waste dumps was combined with fertilization, organic matter accumulation and biological stabilization measures designed to improve soil fertility and reduce erosion risk. Some of the actions that PPC applies for soil rehabilitation are described by LCWM, 2018:

- Shaping of the surface and slopes. Measures for the avoidance of landslides.
- Mixing ash with the remaining infertile materials and depositing it in mines, according to the approved Extractive Waste Management Plan.
- Intermediary materials, rich in organic content, are sent to the upper layer of the deposition.
- Preservation of soil material (soil for plants) and laying of soil material on final surfaces, where necessary, for the support of the intended land use.

- Cultivation of saplings for environmental rehabilitation, for wood production and for the formulation of livestock zones.
- Construction of fencing.
- Cultivation with forest species. For the reforestations are usually used acacia species (*Robinia pseudoacacia*), since according to studies is the most appropriate option due to its properties. It reduces erosion, has a high degree of planting success (90%), an impressive ability to exploit infertile soils and has no need of special care. Also, there is the possibility of producing wood fuel as well as in the flowering period it supports beekeeping. In the wider area there are at least 15,000 acres of acacia that consist of the largest forest of acacia species in our country. Also, the phytosociology of the area is examined, and a big number of deciduous and evergreen saplings is planted in a sparse grid so that their growth will not prevent farmers from using the land. The tree species that have been planted are Arizona Cupressus, cyresses, pines, leylands, cataplas, *Fraxinus*, birches and maples.
- Grading areas for agricultural use. An experimental orchard of 62 acres with pilot cultivations of pear trees, apple trees, cherry trees, quince trees, quince trees and vineyards. The orchard has existed since 2001 according to the principles of systematic agriculture. The fruits are distributed to institutions, local bodies and employees of the Lignite Centre of Western Macedonia. Furthermore, in recent years, the cultivation of aromatic plants has been developed in the rehabilitated deposit of the Main Field Mine and in Amyntaion mining area. The cultivated species that are tested are lavender and lemon balm.
- Areas for beekeeping

Vegetation establishment played a key role in the rehabilitation process. Large-scale plantations of *Robinia pseudoacacia* L. (black locust) were widely used to stabilize slopes and improve soil conditions due to their rapid growth and nitrogen-fixing capacity (Basnou, 2016). More than 1,500 hectares were reforested with average plantation densities of approximately 2,000 trees per hectare (Figure 19).



Figure 19. *Robinia pseudoacacia* L. plantations for slope stabilization and erosion control in Amynteon mine.

The introduction of vegetation significantly improved soil stability, reduced erosion intensity and accelerated biomass accumulation on spoil materials. Although black locust is considered a non-native species and may raise biodiversity concerns, its use under specific conditions provided important short-term reclamation benefits (Papadopoulou et al., 2018).

More recent reclamation approaches increasingly emphasize the use of mixed and native vegetation systems to improve long-term ecosystem resilience, biodiversity and soil recovery processes.

The case of Western Macedonia demonstrates that post-mining soils affected by large-scale lignite extraction can gradually regain agricultural and ecological functionality through integrated reclamation and soil rehabilitation measures. Agricultural reclamation, combined with technical soil improvement, vegetation establishment and long-term land management, enabled the conversion of reclaimed mining areas into productive agricultural landscapes. The experience of Western Macedonia also highlights the importance of adapting reclamation strategies to local climatic and hydrological conditions to ensure long-term sustainability of restored post-mining ecosystems.

8.2. Agricultural reclamation and soil rehabilitation in the Megalopolis Lignite Centre

The Lignite Centre of Megalopolis (LCM), located in the central Peloponnese region of Greece, includes several major open-pit lignite mines, including Thoknia, Marathousa, Kyparissia and Choremi. Mining activities significantly transformed the landscape and disturbed large agricultural and natural areas within the region (PPC, 2016; Sokratidou et al., 2018).

As mining operations gradually entered the closure phase, increasing emphasis was placed on reclamation and post-mining land rehabilitation. The reclamation strategy implemented in Megalopolis combines soil reconstruction, agricultural reuse, afforestation and hydrological restoration in order to create multifunctional post-mining landscapes adapted to local environmental and socio-economic conditions.

8.2.1. Soil rehabilitation and land reconstruction

Rehabilitation activities initially focused on the external waste deposits of the Thoknia and Choremi mines, where more than 6.5 km² were reclaimed between 2004 and 2012. Reclamation measures included technical reshaping of dump surfaces, stabilization of degraded substrates and large-scale vegetation establishment (Louloudis, 2017; Sokratidou et al., 2018).

Vegetation used during the early reclamation stages included species such as *Robinia pseudoacacia*, *Cupressus arizonica*, *Pinus pinea* and *Eucalyptus* sp., selected primarily for their rapid growth, resilience and low maintenance requirements under degraded soil conditions. Additional species included *Pinus halepensis*, *Spartium junceum*, *Olea europaea*, *Castanea sativa* and *Juglans regia* (Louloudis, 2017; Sokratidou et al., 2018).

The establishment of vegetation contributed to erosion control, stabilization of spoil materials and gradual improvement of soil conditions through biomass accumulation and biological activity. These activities formed the basis for subsequent agricultural reclamation and long-term land reuse.

8.2.2. Agricultural reclamation practices

Agricultural reclamation constitutes one of the principal post-mining land-use directions within the Megalopolis lignite region. By 2020, approximately 2,300 acres of reclaimed agricultural land had been restored and leased to local farmers, while future reclamation plans include an additional 7.8 km² designated for agricultural use (IENE, 2020; Sokratidou et al., 2018).

Experimental agricultural cultivation on reclaimed mine soils produced highly satisfactory results comparable to surrounding unaffected agricultural areas. Crops tested included tomatoes, potatoes, beans, oats, grains and vetch (PPC, 2009). These results demonstrate that reclaimed mine substrates in Megalopolis can gradually regain productive agricultural functionality when appropriate soil rehabilitation measures are applied.

Reclamation planning increasingly emphasizes diversified and multifunctional agricultural systems. One of the major projects implemented in the Choremi mine area involves the division of reclaimed land into ten agricultural plots supported by dedicated road infrastructure, six irrigation reservoirs and hedgerow systems designed to function as windbreaks and biodiversity corridors (Figures 20-21) (Sokratidou et al., 2018).



Figures 20-21. The Choremi mine plantation & maintenance works (external deposits) (Sokratidou et al., 2018).

The integration of irrigation systems, water-retention infrastructure and vegetation barriers is particularly important under Mediterranean climatic conditions characterized by seasonal drought and elevated erosion susceptibility.

An important factor is the integration of hydrological management with soil rehabilitation and agricultural planning is considered essential for ensuring the long-term sustainability of reclaimed agricultural systems in the region.

The Megalopolis Lignite Centre represents an example of integrated post-mining reclamation where soil rehabilitation, agricultural reuse and hydrological restoration are implemented simultaneously within a multifunctional landscape framework. Technical stabilization of spoil materials, vegetation establishment and agricultural soil reconstruction enabled reclaimed mining areas to regain productive capacity and support long-term agricultural use.

The experience of Megalopolis demonstrates that even heavily transformed lignite-mining landscapes can be progressively converted into stable agricultural and ecological systems when reclamation activities are integrated with water management and long-term land-use planning.

9. TRANSITIONAL USE OF ENERGY CROPS FOR SOIL REHABILITATION PRIOR TO FOOD CROP PRODUCTION

The agricultural reclamation of degraded and post-mining land requires long-term strategies capable of simultaneously improving soil quality, reducing environmental risks and supporting economically viable land use. One approach increasingly discussed and proposed by the COFA Project involves the temporary cultivation of energy crops as an intermediate stage between technical reclamation and the eventual establishment of conventional food-oriented agriculture.

Energy crops may provide multiple environmental and economic functions during this transitional phase. Besides biomass production for renewable energy purposes, many species demonstrate high tolerance to degraded soil conditions, strong biomass productivity and the ability to support phytoremediation and soil rehabilitation processes. As a result, the cultivation of energy crops may contribute simultaneously to soil improvement, stabilization of degraded substrates, reduction of contaminant mobility and generation of economic value from otherwise low-productivity land.

9.1. Phytoremediation and soil rehabilitation functions

Phytoremediation is considered one of the most important biological methods for the rehabilitation of degraded and contaminated soils, including post-mining and post-industrial areas. The process utilizes plants and associated soil microorganisms to improve soil quality and reduce contamination levels through natural biological and biochemical mechanisms.

The technology is primarily applied in situ and relies on solar-driven hydraulic and metabolic processes occurring within plants and the rhizosphere. Phytoremediation mechanisms include phytoextraction, rhizofiltration, phytodegradation, phytostabilization, phytovolatilization, hydraulic control and rhizodegradation. The effectiveness of these mechanisms depends on the type of contamination, soil conditions, climatic factors and the selected plant species (Eskander & Saleh, 2015). In degraded mining soils, plants contribute to remediation processes through several mechanisms:

- uptake and accumulation of heavy metals and chemical compounds,
- stabilization of contaminated substrates,
- stimulation of microbial activity within the rhizosphere,
- improvement of soil structure and biological activity,
- enhancement of soil organic matter accumulation.

The rhizosphere plays a particularly important role in degradation of organic contaminants such as petroleum hydrocarbons and PAHs. Root exudates stimulate microbial activity and support enzymatic degradation processes involving enzymes such as dehalogenases, peroxidases and laccases (Schnoor et al., 1995). Grasses belonging to the *Poaceae* family were shown to be particularly effective in supporting degradation of hydrocarbon contaminants in soil (Olson et al., 2007; Cooks & Hesterberg, 2013). Phytoremediation remains a relatively slow process and may require several years or even decades depending on contamination type and concentration. Nevertheless, the combination of phytoremediation with biomass production creates opportunities for simultaneous environmental rehabilitation and economic utilization of degraded land.

9.2. Energy crops as transitional reclamation systems

The dual-function approach combining phytoremediation and biomass production represents one of the most promising directions in sustainable reclamation of post-mining soils. Fast-growing energy crops are capable of producing high biomass yields under relatively poor soil conditions while

simultaneously improving soil quality and reducing environmental risks associated with contamination.

This approach combines environmentally friendly reclamation with the production of local renewable energy resources, potentially reducing dependence on external energy supplies while supporting the gradual recovery of soil functionality (Hauptvogel et al., 2020). Many energy crop species demonstrate:

- rapid biomass accumulation,
- tolerance to abiotic stress,
- extensive root system development,
- high nutrient uptake capacity,
- ability to accumulate or stabilize contaminants,
- positive influence on soil organic matter and microbial communities.

An additional advantage is that energy crops are generally not intended for direct food-chain introduction, which reduces risks associated with cultivation on soils that may still contain elevated contaminant concentrations.

9.3. Selected energy crops for reclaimed and contaminated soils

Several energy crop species are considered particularly suitable for post-mining and degraded land rehabilitation under Central European conditions.

9.3.1. *Miscanthus × giganteus*

Miscanthus is characterized by very rapid growth, reaching heights of 3-4 m annually, together with high biomass productivity and relatively low maintenance requirements after establishment. The species demonstrates good drought tolerance and is widely used for pellet and biomass fuel production.



Figure 22. Plantation of giant miscanthus (*Miscanthus × giganteus*).

Source: [Terravesta](#)

9.3.2. Energy Willow (*Salix spp.*)

Energy willow is one of the fastest-growing woody energy crops and is commonly cultivated in short-rotation systems. The species tolerates relatively moist soils and develops extensive root systems contributing to substrate stabilization and contaminant uptake.



Figure 23. Harvesting of energy willow (*Salix viminalis* L.).
Source: [Agriland](#)

9.3.3. Energy Poplar (*Populus spp.*)

Poplar plantations are characterized by rapid wood production and high biomass yields suitable for short-rotation forestry systems. Poplar species are also frequently discussed in phytoremediation applications due to their extensive root systems and high transpiration capacity.

9.3.4. Virginia Mallow (*Sida hermaphrodita*)

Virginia mallow is a perennial species characterized by rapid growth, frost resistance and high dry biomass production. The species is increasingly considered for biomass production on lower-quality soils.

9.4. Soil microorganisms and rhizosphere interactions

The effectiveness of phytoremediation and biomass production depends not only on plant species selection but also on interactions with rhizosphere microorganisms. Plant growth-promoting bacteria (PGPB) may significantly improve biomass production and increase plant tolerance to heavy metal stress.

Studies involving bacteria such as *Burkholderia* sp., *Bacillus megaterium* and *Sphingomonas* sp. demonstrated enhanced growth and increased metal accumulation capacity in energy crops cultivated on contaminated soils (Sun et al., 2010). Rhizosphere microorganisms may:

- stimulate plant growth,
- increase nutrient availability,
- reduce heavy metal toxicity,
- improve stress tolerance,
- accelerate contaminant degradation processes.

Consequently, future reclamation systems may increasingly combine energy crops with engineered microbiological support systems in order to accelerate soil rehabilitation and biomass productivity.

9.5. Biomass production and Circular Economy potential

The cultivation of energy crops on reclaimed land creates opportunities for simultaneous environmental rehabilitation and renewable energy production. Biomass harvested from reclamation plantations may be utilized for pellet production, district heating systems, bioenergy generation or industrial biomass applications.

This approach supports circular economy principles by transforming degraded land into productive systems while reducing pressure on high-quality agricultural soils intended for food production. Additionally, long-term cultivation of perennial energy crops contributes to:

- accumulation of soil organic matter,
- carbon sequestration,
- reduction of erosion processes,
- improvement of soil structure,
- enhancement of microbial activity,
- gradual restoration of ecosystem functions.

The temporary cultivation of energy crops may represent an effective transitional strategy for the rehabilitation of degraded and post-mining soils prior to conventional agricultural use. Energy crops combine several important functions simultaneously, including phytoremediation, soil stabilization, biomass production, carbon sequestration and ecosystem restoration.

The integration of fast-growing biomass species with phytoremediation and rhizosphere-support processes creates opportunities for economically productive reclamation systems capable of improving soil quality over long time scales. Such approaches may significantly support the transformation of degraded post-industrial landscapes into stable agricultural and ecological systems while contributing to renewable energy production and climate-change mitigation objectives.

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