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Review

Technosols for Mine Restoration: Overcoming Challenges and Maximising Benefit

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Abstract

The escalating demand for non-renewable resources is anticipated to intensify extractive activities, which are invariably associated with significant environmental externalities. The rehabilitation of mined landscapes, undertaken to mitigate ecological degradation and reinstate ecosystem functions and biodiversity, is frequently constrained by substantial financial requirements as well as intricate technical, logistical, and environmental challenges. As a consequence, a considerable proportion of extractive sites worldwide remain unreclaimed. There is a critical need for sustainable, cost-effective, and versatile restoration practices. This article presents a bibliographic review focusing on problems encountered in mine remediation and the role of technosols in addressing these issues. Mine restoration initiatives are confronted with a suite of interrelated challenges, including suboptimal soil physicochemical characteristics, hydrological instability, geomorphological hazards, and the exacerbating effects of extreme climatic events. Technosols, formulated from various waste materials, prove to be a versatile and cost-effective biotechnology that can significantly improve soil fertility, reduce erosion, enhance water retention, and restore biological activity. Their application, which can include mining waste and organic residues, substantially lowers costs estimated globally at EUR 829.711 billion for soil formation and contributes to a circular economy. Technosols represent a promising and efficient biotechnology for mine restoration. Their use facilitates the creation of stable, functional, and self-sustaining landscapes, enabling not only environmental recovery but also social and economic benefits through post-restoration land uses. Further research and knowledge transfer are vital for their broader and optimised implementation.

Keywords: abandoned mine; topsoil; reclamation; risks; climate change; logistical challenge; vandalism

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Academic Editor: Dongmei Zhou

Received: 25 August 2025
Revised: 22 October 2025
Accepted: 29 October 2025
Published: 31 October 2025

Citation: Rodríguez-Espinosa, T.; Pérez-Gimeno, A.; Almendro-Candel, M.B.; Navarro-Pedreño, J.; García-Fernández, G. Technosols for Mine Restoration: Overcoming Challenges and Maximising Benefit. *Appl. Sci.* **2025**, *15*, 11664. https://doi.org/10.3390/app152111664

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1. Introduction

Extractive activity provides essential resources for the evolution and development of human activities [1–3]. The demand for non-renewable resources has exhibited a sustained upward trajectory and is projected to intensify further, driven in part by contemporary global tensions that increasingly magnify the interplay between geopolitical dynamics, supply security, and extractive requirements. These pressures are compounded by factors such as climate change, the imperatives of the low-carbon transition, armed conflicts, global

health crises, and the proliferation of protectionist measures [4–7]. The energy transition (wind energy, photovoltaics, electric vehicles, storage systems) shows a scenario of a five-fold increase in demand for lithium and two-fold increases for graphite, nickel, cobalt and rare earths from 2025 to 2040. Moreover, it will require a large investment for the exploitation of new mines and associated industries [8]. The study published by Maus et al. [3] quantified the area occupied by mining activities globally at 101,583.4 km^2 in 2022. They often develop in ecosystems rich in biodiversity or with high agricultural potential [9–13].

The environmental impacts associated with the exploitation of a mining site throughout all stages of activity (exploration, construction, production) and closure are considerable [1,10,14,15]. One of the most controversial aspects of a mine is the large amount of waste generated, as well as its impact on soil and vegetation [16,17]. In 2022, the mining sector accounted for approximately 23% of total waste generation within the European Union, positioning it as the second-largest contributor after the construction industry, which generated 38% [18]. The expected growth in mining activity will therefore lead to an increase in the EU mineral footprint [4]. By 2040, it is anticipated that over 80% of direct and indirect greenhouse gas emissions occurring outside the European Union will be attributable to the mining sector [4].

The European Union, cognisant of the environmental challenges associated with extractive industries, has advocated the adoption of advanced techniques and technologies as a mitigation strategy to reduce the sector's ecological footprint. Such approaches include so-called 'green mining' innovations, which are oriented towards ecological restoration and the progressive realisation of zero-waste objectives [14]. Environmental restoration is defined as the process of halting and reversing degradation, resulting in improved ecosystem service provision and the recovery of biodiversity [15,19]. Ecosystem restoration encompasses a wide continuum of practices, depending on local conditions and societal choice. Ensuring the recovery of pre-mining ecosystems necessitates rigorous planning, active stakeholder engagement, compliance with regulatory frameworks, and the acquisition of relevant permits. Additionally, the development of a comprehensive inventory and other supporting measures is considered essential to optimise restoration outcomes [20,21]. Contingencies or unforeseen events often arise during extractive development and restoration. Despite the importance of dealing with these overbooked situations with technical competence [20], few articles or bibliographic references address this issue.

In addition, abandoned/orphaned unrestored, or incomplete or negligently restored mines are common [22,23]. The number of abandoned mines worldwide is estimated at around the millions [24]. By country, the USA accounts for 550,000 abandoned mines, Europe over 100,000 sites, Australia more than 50,000 abandoned sites, and in South Africa, there are around 6000 [25,26]. Although comprehensive national data remain unavailable, sector-specific records in China indicate the registration of approximately 2800 abandoned coal mines and 300 abandoned gold mines [27,28]. This widespread situation is mainly due to the high costs associated with restoration work, estimated at EUR 35 per capita per year in the EU for soil remediation, EUR 0.32–2.5 per m^2 for restoration and EUR 250–400 per m^2 for reclamation (making disturbed land suitable for a new human-driven use) [15,29,30]. Project costs may be elevated by the emergence of unanticipated challenges arising either during the restoration process itself or throughout subsequent monitoring activities. However, a restoration that succeeds in restoring ecosystem functionality enhances the safety and well-being of the ecosystem (biodiversity) and people (e.g., flood control, storm buffering, carbon sequestration, recreational uses), not only recovers the initial investment but also generates substantial benefits [30,31]. Ensuring compliance with the legal obligations of mine restoration, applicable to both newly established and abandoned sites, together

with promoting economic development and implementing effective restorative practices, may therefore be regarded as a priority.

Thus, it is necessary to apply sustainable techniques that are less costly than the usual ones, that can be versatile to adapt to the great variety of possible restoration circumstances even in the same extractive area, that can solve problems, that are technically and logistically feasible, that can be replicable and that, in addition, can ensure the ecosystemic, social and economic functionality of the area [32,33]. The formulation of technosols, a substrate derived from waste materials that retains all the functionality of natural soil, but with a strong human influence on its formation, is being applied in mining restoration recently [34,35]. While these soils exhibit all the aforementioned characteristics, further empirical investigation and the development of a practical guide for restoration practitioners remain necessary [23,36]. The application of technosols for mine restoration is achieving promising results. However, the use of residues from the extractive activity itself (rocks, soil, tailings) may have certain limitations, such as the scarcity of organic matter and nutrients or the presence of trace elements [37,38]. Therefore, wastes with high concentrations of organic matter, such as composted sewage sludge and agri-food wastes, as well as wastes capable of immobilising trace elements, are also incorporated into mine reclamation [38–41].

This article provides a review of the application of technosols to solve the technical and environmental problems of mine and quarry land reclamation. This is centred on addressing the contingencies that can arise in mine restoration and the role that technosols can play in preventing and mitigating them. It is carried out from a broad perspective in which mining reclamation using technosols approaches its design, taking into account the potential environmental, social and economic uses and benefits of the restored area.

2. Materials and Methods

Articles were included in the literature review based on the following criteria: (i) research/papers/studies related to problems encountered or associated with mine remediation and the use of technosols to address them; (ii) articles published since 1999; (iii) methodical demonstration and synthesis of findings; (iv) priority was given to studies with a global geographical scope. If a limited sample of global studies existed, national or regional studies were also considered; (v) studies presenting thorough outcomes and/or information for an integrated approach to the subject; (vi) records found using the specified keywords.

To assemble the bibliography supporting the literature review, the primary objective was to conduct documentary research, which involves the systematic compilation and examination of existing information relevant to the topic or problem under consideration. To do this, the Scopus database was consulted. The search options were title, abstract and keywords. The following keywords were used (combined or separately): *restoration problem*, *mine and quarry restoration*, *technosols*, *abandoned mine*, *geomorphology*, *hydrology*, *soil*, *vegetation and fauna*, *use*, *reclamation*, *land*, *costs*, *social*, *economic*, *regulation*, *objectives*, *methodology*, *biotechnology*, *risks*, *climate change*, *vandalism*, *landform*, *herbivory*, *runoff*, *structural instability*, *prevention*, *strategies*, *sustainability* and *circular economy*.

3. Technical and Other Problems in Mine Restoration

The multidisciplinary team in charge of mine restoration must select the most advantageous restoration methods, in the interests of sustainability, technical and economic feasibility and safety [21]. This is not an easy task, especially when dealing with abandoned mines (Figure 1). In such instances, legal accountability is often fragmented, and the implementation of remedial measures typically demands considerable financial investment, together with the mobilisation of specialised personnel, technical expertise, and adequate

infrastructure. In addition, degradative and contaminating processes may have been exacerbated, even affecting remote areas, and there is scarce or no background on the behaviour of the excavated materials and the actions carried out during the mining process [42–44].



Figure 1. Abandoned clay quarry (Alicante, Spain).

The problems to be solved can vary greatly depending on the type of mine and the resource extracted, if it was abandoned or not, presence of associated constructions (e.g., waste dumps, tailings ponds, roads, buildings), dangerousness of the mining waste, geomorphology (e.g., vertical slopes, open pits, trenches, esplanades), climatic conditions, proximity to inhabited or high environmental value areas, presence of water bodies, among others [45,46]. Therefore, it would be advisable to start with an exhaustive analysis of the characteristics, risks and needs of each area to determine restoration methods [21,45–47]. Sectoral differentiation is likely to prove essential in identifying the specific requirements of each degraded site, thereby necessitating the adoption of diverse and adaptable methodological approaches, allowing for an *à la carte* design. Despite a good analysis of the preconditions and their associated risks, unforeseen events may occur at any time during the restoration process (geomorphological and hydrological action, revegetation or monitoring). In the following, we address the most common technical problems and other contingencies that a mine restoration manager has to deal with (Table 1).

Table 1. Problems or contingencies encountered during mine restoration.

Topic	Contingencies	Reference
Geomorphology	Need for backfill material (scarcity or poor structural capacity of available resources). Presence of mining waste. Presence of exogenous materials (e.g., debris, rubbish, alluvial material, abandoned buildings, pipelines and installations). Existence of steep slopes. Generation of subsidence and caves. Instability and landslides.	[28,41,46,48–54]

Table 1. *Cont.*

Topic	Contingencies	Reference
Hydrology	Excessive surface runoff and erosion. Poor drainage. Inadequate water retention. Surface and groundwater contaminated waters. Presence of water bodies.	[41,43,46,49,54,55]
Soil	Lack of fertile soil or presence of soil with reduced fertility and nutrient content. Inadequate physico-chemical properties. Nonexistent or low soil biodiversity and biological activity. Contaminated areas.	[23,38,46,52,56–58]
Vegetation and fauna	Herbivory and pests. Need to introduce endangered species, non-commercial plant species or species associated with specific substrates. Need to maintain or protect a species or ecosystem. Need to eradicate non-native or invasive species.	[23,49,57,59,60]
Others	Abandoned mine. High costs and not designing restoration for sustainable use (social, environmental and economic). Little or no environmental regulation. Little or no knowledge of the background. Poorly defined restoration objectives or a short-sighted approach to restoration with only landscape-focused benefits, without economic, social and environmental benefits. Poor monitoring of the evolution of the restoration or not prolonged over time. Lack of knowledge of new biotechnology systems. Pollution affecting areas away from the mine. Unfavourable climatic conditions and extreme weather events. Need for services, infrastructure and equipment. Logistical and access to the area problems. Large area to restore that has a diversity of zones with different characteristics and needs. The non-involvement of scientific teams or local inhabitants. Vandalism and the presence of passers-by or footpaths.	[23,28,43,58,60]

The landforms that traditionally result from mining cuts and spoil banks usually present linear geometric topography [48]. While certain regular geometric forms do occur in nature, natural systems predominantly exhibit more complex morphologies, including fractals, spirals, and irregular patterns. Accordingly, geomorphological design should transition from linear and simplified configurations towards circular and more intricate structures, particularly in arid and semi-arid environments, in order to mitigate the susceptibility of landscapes to geomorphic hazards [44,55,61]. Moreover, considerations of structural integrity and the operational safety of personnel remain essential. Geomorphological modelling programmes are now available to develop a new landscape that avoids terracing, prevents water erosion processes and shows the morphology of the area as it evolves over the centuries [61]. Effective mine restoration often requires significant volumes of backfill material to re-establish the original topography, fill voids, and prevent subsidence [52,61]. A primary challenge is the scarcity of suitable on-site materials or the poor structural capacity of what is available, such as mine tailings or waste rock [58]. Although mine waste is often used, even for structural securing [54], while tailings can be used as a backfill source, they often have low shear strength and poor consolidation

properties, making them unsuitable for creating structurally stable landforms without significant treatment. Another concern about the use or presence of mining waste in geomorphological restoration is its potential for pollution [58]. Acid mine drainage, where water reacts with sulphur-bearing minerals to produce sulfuric acid and leached metals, can also be a significant issue in certain rock types [38]. These pollutants can harm aquatic life, contaminate drinking water sources, limit plan development and negatively impact the overall health of the surrounding ecosystem. A suitable geomorphological design with sinuous shapes will prevent the appearance of problems such as gullies, landslides, slope movements, subsidence or the formation of galleries, spread of pollution to aquatic areas by runoffs, etc. [44,48,53]. Moreover, it will therefore contribute to the good development of the other restoration phases and avoid delays and higher costs [48,52,60]. Geochemical modelling for mine site characterisation and remediation is also needed. However, these predictions also suffer from certain limitations, such as the need for the technician to have extensive knowledge in various areas and that the predictions may not be realistic, especially in large-scale and extensive mining areas [61,62].

Quarry and mine restoration sites often suffer from excessive surface runoff and erosion due to a lack of vegetation and compacted, barren soils [41,55,61]. In addition, excavated mines and rivers can be severely affected by mining activity and are flood-prone [44]. Long and large-angle slopes created by mining activities are unstable and highly susceptible to water flow that removes vital topsoil and nutrients and also transports sediment into nearby water bodies, degrading aquatic habitats and increasing turbidity [44,61]. The high runoff volumes prevent water from infiltrating the soil, hindering plant growth and creating arid conditions. This process perpetuates a cycle of low vegetative cover and further erosion, making long-term restoration difficult. The loss of topsoil is particularly damaging, as it is the foundation for a healthy ecosystem [55]. Due to surface runoff, breakage of the slope structure is quite common (gullies and landslides), and appears very quickly, due to low material cohesion, especially in areas with a Mediterranean climate [44,55,61] (Figure 2). This facilitates the monitoring of surface runoff dynamics and enables the rectification of potential issues prior to the integration of fertile soil or the commencement of seeding. Such early intervention is critical, as alterations to site morphology become markedly more challenging at advanced stages of ecological restoration. It is therefore advisable to allow a moderate amount of time after geostructuring to detect incipient problems, but not too much to avoid an increase in erosion processes.



(**a**) (**b**)

Figure 2. Presence of a gully (**a**) and possible landslide of part of a restored mine slope (**b**) (Alicante, Spain).

However, the presence of large esplanades, usually on the tops of slopes, entails risks which, in our experience, are just as dangerous and complicated to resolve as those that

occur on the slopes. These processes have received comparatively limited attention in the literature. They include the development of surface streams traversing esplanades and running parallel to slopes, as well as the formation of subsurface galleries within the fill material induced by water movement (Figure 3). Such phenomena typically emerge over extended timescales, being driven by compaction and settlement processes within the backfill [55]. Alterations to drainage gradients arising from settlement can redirect rainfall into unanticipated runoff pathways or promote its accumulation on the esplanade. The retention of rainwater on the platform, in turn, exacerbates compaction and settlement, facilitating further infiltration into the backfill, particularly where cohesion is low [41]. Infiltrating water can also mobilise finer particles within the fill, rendering subsurface flow pathways highly unpredictable. If its path involves leaving at the base of a slope, this creates additional problems. The presence of holes in the esplanade is the main symptom to detect this type of unforeseen event (Figure 3b). The only effective way to correct the problem is to act geomorphologically after the settlements. This situation is highly undesirable when hazardous waste is present.



(**a**) (**b**)

Figure 3. Presence of a stream next to a slope (**a**) and an underground gallery hole in a restored mine esplanade (**b**). (Alicante, Spain).

Poor rainwater drainage is a significant issue in many quarries and mines, often stemming from the compaction of subsoils and the creation of hardpans during excavation and backfilling [61]. This compaction limits water infiltration, leading to waterlogging in some areas and excessive runoff in others [44]. Waterlogged conditions can kill plant roots, while the lack of soil permeability in other zones prevents the establishment of a healthy plant community. The problem is exacerbated by the often-heterogeneous nature of quarry backfill, which can contain a mix of materials with varying permeability. The absence of an efficient natural or artificial drainage system can lead to stagnant water accumulation, which negatively impacts soil stability and the viability of the ecosystem. Mines typically have soils with low organic matter content and poor structure, because mining removes or buries the nutrient-rich topsoil layer, leading to inadequate water retention [52,60]. The sandy or rocky nature of many quarry soils means they lack essential nutrients and have a limited capacity to hold water, causing them to dry out quickly after rainfall [52,58,61]. This makes it difficult for plants to establish, grow and survive, especially during dry seasons or droughts [41,61]. Without sufficient water retention, newly planted vegetation experiences water stress, leading to high mortality rates and hindering the establishment of a self-sustaining ecosystem [61]. The lack of vegetative cover, in turn, exacerbates erosion and runoff issues, creating a vicious cycle of soil degradation [58].

Soils in mines often have deficient physicochemical properties that inhibit plant growth [41,52,58]. The pH can be extremely acidic (from acid mine drainage) or alkaline, which limits nutrient availability and can be harmful to most plant species. Low cation

exchange capacity (CEC) means the soil cannot effectively retain nutrients, making them vulnerable to leaching. Soil compaction constrains root penetration, impedes gas exchange, and reduces water infiltration. The presence of trace elements or contaminants, particularly heavy metals such as lead and cadmium, and other elements like arsenic, may exert toxic effects on plants and soil biota [41,58]. In addition, mine substrates frequently exhibit unfavourable textural and structural characteristics, often dominated by excessive sand or clay fractions and lacking the aggregation necessary to sustain soil functionality. The widespread use of mining residues in geomorphological rehabilitation further complicates predictive assessments of long-term behaviour, not only in terms of geotechnical stability but also concerning surface evolution and pedogenesis [61]. Mining activity also disrupts soil food webs, severely diminishing biodiversity and biological functioning [28]. As a result, post-mining soils are frequently biologically inert, being depleted of beneficial microorganisms, including bacteria, fungi, nematodes, and earthworms, that are essential for nutrient cycling, aggregate formation, organic matter turnover, and the regulation of soil-borne pathogens [58]. Without this soil life, plants cannot form symbiotic relationships with microorganisms (like mycorrhizae) that are vital for nutrient uptake. The absence of organic matter and extreme physicochemical conditions inhibit the return of biological life, preventing the soil from becoming a functional ecosystem.

Heavy rainfall can overwhelm a site's drainage system, leading to severe erosion, landslides, and the washing away of newly planted vegetation and soil amendments [44,63]. Mine pits and fluvial systems are also subject to alterations induced by mining activities, which may render them particularly susceptible to flooding during episodes of intense precipitation [44]. Conversely, prolonged droughts can cause newly established plants to die, leading to soil desiccation and increased vulnerability to wind erosion. Strong winds can also strip topsoil and spread dust, affecting air quality. Harsh climatic conditions and climate change add further complexity to mine restoration [58,61]. More frequent extreme weather events can significantly impact the stability of restored sites. Conventional restoration methods, with their uniform slopes and rigid drains, are often overwhelmed by these extreme events, leading to catastrophic failures [44].

One of the most significant challenges in mine revegetation is controlling herbivory and pests [64]. Newly planted vegetation and seeds are an easy target for local herbivores, which can consume large numbers of seedlings and young trees, frustrating restoration efforts. In some cases, we have suffered a high percentage of plant death due to the presence of rabbits. Protective guards proved insufficient as deterrent barriers, since fauna were observed to dig around and even uproot seedlings (Figure 4a). Furthermore, insect pests may infest and weaken plants, thereby increasing their susceptibility to water stress and disease. In the absence of a critical mass of established vegetation, such biotic pressures can be particularly detrimental, often resulting in elevated mortality rates [64]. While plant mortality is commonly assessed in the short term, longer-term dynamics are influenced by a broader range of interacting factors that may further exacerbate losses [64]. Constant monitoring and implementing control measures are essential to protect the restoration investment. Reintroducing endangered or non-commercial plant species to a restoration site is often a crucial goal. These species may have specific habitat requirements that are difficult to replicate in the degraded soil of a mine, e.g., vegetation associated with specific substrates (dolomite, serpentine, copper or gypsum soils) [52,57]. Their survival depends on precise pH, nutrient, and soil structure conditions. Furthermore, seed sources or individuals for planting of the vegetation associated with these specific substrates can be scarce and difficult to obtain. Success requires careful planning, from collecting and propagating seeds to planting young individuals, ensuring they are given the optimal conditions for establishment and growth. Mining sites often host unique species or ecosystems that

have survived the disturbance or have even adapted to the extreme conditions. This could include rare species of lichens, mosses, or even specific fauna that use the rocky structures. Restoration planning must balance the need to revegetate the site with the protection of these existing elements. If restoration focuses solely on mass planting of common species, there is a risk of eradicating the unique ecological niches that have already managed to establish themselves [65]. Protecting these "survivors" requires detailed mapping and creating exclusion zones, ensuring the restoration design does not harm existing biodiversity. Before restoration efforts begin, it is common for alien or invasive plant species to have colonised the site, taking advantage of disturbed conditions and lack of competition. These species, such as invasive weeds or fast-growing non-native trees, can outcompete and displace the native species that are being introduced [66]. Once established, they are difficult to eradicate and can alter soil composition and nutrient cycles, making restoration nearly impossible.



(**a**) (**b**)

Figure 4. Plant root ball uprooted by herbivore digging (**a**) and temporary stockpiling area for planting trays (**b**) (Alicante, Spain).

Vandalism poses a significant threat to mine restoration projects, especially those located near urban areas or with easy access. Acts of vandalism, such as pulling up seedlings, damaging fences or signs, stealing material and fuel, leaving rubbish or using the site for unauthorised activities (like off-road vehicles), can reverse years of work and investment [23,59]. In the restoration of large mining areas, which require large quantities of species for planting, it can be difficult not to have an area for storing and watering the trays (Figure 4b). Moreover, mined sites are often littered with anthropogenic debris, especially in the abandoned ones, including infrastructure, buildings, pipes, and other waste [23]. These exogenous materials must be carefully managed as they can act as zones of weakness, inhibit natural soil development, and contaminate the site. In some cases, these materials can be integrated into the restoration plan if their presence does not compromise the final landform's stability or long-term ecological function or has a cultural or heritage interest. However, the standard approach is to remove and properly dispose of these materials in a way that does not interfere with the hydrological or geomorphological integrity. In addition to destroying vegetation, vandalism can compact the soil, introduce contaminants, or damage erosion control infrastructure. It is also a risk to their physical integrity, especially if they gain access when heavy machinery is working and clearing or moving material is being carried out. Effective prevention necessitates a multifaceted approach, incorporating measures such as the installation of fencing and signage, routine site monitoring, and community engagement initiatives aimed at fostering a sense of stewardship and protection for the restored area [61]. The presence of unauthorised individuals or existing pathways on a mine site presents a complex logistical issue. Restored areas need to be protected from

disturbance, but if the site has historically been used as a shortcut or recreational area, it can be difficult to manage. Unauthorised access can lead to soil compaction, damage to plants, and the introduction of invasive species. Managing this requires a delicate balance: while restricting access is necessary for restoration, it can also lead to conflict with local communities. Solutions require clear signage, fencing, and, in some cases, the creation of designated public access areas to redirect foot traffic and prevent damage.

Mine restoration is an infrastructure-heavy undertaking. Projects require a wide range of specialised equipment, from heavy machinery for earthworks to hydroseeding trucks and irrigation systems. Acquiring, transporting, and maintaining this equipment, especially on remote or difficult-to-access sites, is a major logistical challenge. The lack of existing infrastructure, such as paved roads, reliable power, or water sources, necessitates building these from scratch, which adds significant cost and complexity. Poor road conditions can delay the delivery of materials and increase vehicle wear, making daily operations more difficult. This becomes even more complicated when we are faced with a large area to restore that has a diversity of zones with different characteristics and needs [58]. Sometimes, the restoration of mines or quarries, by legal imperative, is focused on making the minimum investment to mimic the landscape (it is a make-up process), intending to recover the bond initially required for the exploitation concession. In general, mine restoration may not achieve the desired objectives [28]. This means that the ecosystem cannot recover, and new problems will appear over time.

4. Technosols

One of the first definitions that expressly indicated the concept of Technosols is "other soils dominated by technogenic soil materials (refers to all anthropo-geomorphic soil materials created as the result of technical processes) a depth of 100 cm or a lithic or para-lithic contact, whichever is shallower" [67]. Lehman [68] highlights the close relationship of Technosols with urban soils: "having technic soil material with an artefact content by volume of more than 50% for a depth of at least 10 cm, starting within 10 cm from the soil surface". Technic soil is considered as "soil material showing evidence of urban, industrial and related activities, and evidence is visible by a content of artefacts by volume equal to or more than 20%".

Human activities take place on the ground, so they inevitably have an impact on it. Soils exhibiting substantial anthropogenic influence have, in fact, been formally incorporated into the World Reference Base for Soil Resources (WRB) under the classification of Technosols [69]. Technosols comprise "soils whose properties and soil formation are dominated by their technical origin. They contain a significant amount of artefacts (>20% by volume, weight-weighted, of artefacts in the top 100 cm of the soil surface or down to continuous rock), artefacts being something in the soil that is recognisably made or heavily altered by humans or extracted from greater depths; or are sealed by hard technical material (hard material created by humans that has properties different from natural rock) or contain a geomembrane. They include waste soils (landfills, sludge, slag, mine waste or debris, and ash), pavements with their underlying unconsolidated materials, soils with geomembranes, and artificially constructed soils" [69].

Therefore, this classification considers technosols to be soils that are modified by humans, as well as those that humans formulate and develop with the intention of creating technical soils; i.e., soils that do not obey the normal development under the soil-forming factors of the specific area, but are created expressly to respond to existing problems. Due to the wide-ranging benefits of its application, recent manuscripts provide definitions that are more focused on highlighting its environmental functionality [70,71]. One of the most comprehensive definitions considers technosols to be soils designed with the

intention of providing ecosystem services equal to those offered by natural soils, or to enhance an ecosystem service; therefore, it would surpass natural soils, ensuring human and environmental health.

Since 2005, scholarly interest in technosols has steadily increased, with a marked rise in publications observed between 2013 and 2020 [34]. Initial studies primarily addressed their application in urban environments; however, since 2010, there has been a discernible shift towards exploring their potential in mining contexts. Technosols are also being investigated for use in agriculture, landfill rehabilitation, aquaculture, and even recreational infrastructure such as golf courses [34]. This growing body of research suggests that interest in both the study and practical implementation of technosols is likely to continue expanding. Notably, the European Union's 2024 report on soil status identifies technosols as a potential strategy for addressing ongoing soil degradation [72]. Although the formal recognition of technosols as a distinct soil category remains relatively recent within the broader history of soil science, the field clearly warrants further systematic investigation.

5. Advantages of Using Technosols in Mine Restoration

The utilisation of technosols formulated from residues originating either from mining operations or ancillary industrial activities offers considerable potential for mine restoration, whether of abandoned or active sites, as outlined in Table 2.

Table 2. Environmental, social and economic benefits of using technosols in mine restoration.

Contribution
Reduce environmental, social and economic risks.
Sustainability on circular economy and zero waste models is promoted.
If regulations are in place for the use of technosols in mine restoration, its use will become more widespread, generating more knowledge.
With a proper project to incorporate the technosols, you can prevent or solve problems as they occur.
Facilitating its use after mine restoration and obtaining benefits beyond the environmental (social and economic).
Reduces mine restoration costs and prevents the occurrence of unforeseen costs.
Reduction in the environmental impact of extractive activities and their extension to other areas.
Technically, more efficient biotechnology.
Suitable for successful mining restoration.
Environmental remediation.
The use of technosols is compatible with the use of electronic tools and software.
Reduce slope runoff and contribute to geotechnical stability.
Enhance food and non-food biomass yield.
Improve soil physico-chemical properties and fertility.
Improves soil resilience: enables greater water retention capacity.
Buffer capacity against soil and water pollutants.
Improve resistance to soil erosion and aggregate stability.
Allows for restoration in areas where fertile soil is scarce.

Table 2. *Cont.*

Contribution
Develop pedogenic processes (soil formation).
Provide ecosystem services (i.e., flood control, carbon storage).
Can be used in terrestrial and aquatic ecosystems (wetlands).
Improving water quality.
Contributes to the development of soil biomass and biodiversity.
Feasible to achieve a specific substrate replicating the reference ecosystem.
Enables better coping with adverse weather events.
By having a standardised methodology for the use and monitoring of the restoration, the benefits of using technosols would be greater.
Enhance the development of alliances and synergies with other activities.
Versatile use in mining restoration.

To make the restoration of abandoned mining activities of interest beyond the public initiative, it would be desirable that these restored areas could even be designed for use (e.g., flood control, storm buffering, carbon sequestration, agroforestry, livestock farming, aquaculture, energy generation and storage, educational and species conservation activities, recreational and tourist activities) (Figure 5) [15,21,23,56,73,74]. Technosols formulated with waste have been successfully applied in the restoration of abandoned mines for environmental remediation in conjunction with agricultural use [36] (Table 3). Given their engineered composition, technosols may be tailored to exhibit greater fertility than the surrounding natural substrates, thereby offering enhanced potential for ecological restoration. Due to their great versatility of formulation, they can meet the agricultural needs of different species in the same restored area and the geomorphological variability of these areas [23].



Figure 5. Quarry abandoned and restored by the regional authorities for the recovery of the species *Aphanius iberus* listed as an endangered (EN) fish species by the IUCN, and endemic to the Iberian Peninsula. In addition, it is used as an environmental education centre (Alicante, Spain).

Table 3. Previous studies on the application of technosols in mines.

Type of Mine	Residues	Formulation or Profile of Technosols	Use and Reference
Limestone	Materials must be conformed both to the Andosols properties, e.g., physical and chemical fertility, and to the olive and vine requirements (well-drained, with a loam/sandy-loam texture and a neutral-alkaline pH). Limestone, zeolitised tuffs and commercial manure.	0 ÷ 20 cm, well drained, common rock fragments, loam, neutral-alkaline. 20 ÷ 40 cm, well drained, common rock fragments, loam, neutral-alkaline. 40 ÷ 80 cm, well drained, common rock fragments, loamy sand, neutral-alkaline. 80 ÷ 120 cm, spolic limestone debris, excessively drained, many rock fragments, coarse gravelly, alkaline.	Agriculture use [23].
Polymetallic sulphide	Polluted soils (PS) by metal(loid)s affected by mining spills and organic and inorganic wastes from mining (iron oxyhydroxide-rich sludge (IO), carbonated waste from peat extraction (CW), and marble cutting and polishing sludge (MS)), from urban activity (composted sewage sludge (WS)), vermicompost from pruning and gardening (VC), and from agro-industry (solid olive mill by-product (OL)).	Six technosols were designed and produced by mixing the polluted soil with a mixture of amendments (%):	Soil remediation and restoration [32].
Sulphide	Two mine wastes mainly composed of gossan (GW) and sulphide-rich wastes (SW) and organic/inorganic wastes from agro-industry (plant remains and substrate—AgW; rockwool used to strawberry crop—RW; residues from liquor distillation—AW; and residues from liquor distillation—CW).	Four technosols: manual mixture of 97% or 94% of GW (fraction < 10 mm) and 3% or 6% of two amendment mixtures containing organic/inorganic.	Soil remediation and restoration [38].
Copper mine	Organic wastes, including mussel residues, wood fragments, sewage sludges and paper mill ashes.	Technosol 1: mussels (70%) and eucalyptus wood fragments (30%). Technosol 2: 50% residues from cleaning mussel rafts and 50% of sewage sludges and ashes from a paper mill.	Soil remediation and restoration [41].

Technosols	PS	IO	CW	MS	OL	WS	VC
T1	60	2	20	-	18	-	-
T2	60	2	20	-	-	18	-
T3	60	2	20	-	-	-	18
T4	60	2	-	20	18	-	-
T5	60	2	-	20	-	18	-
T6	60	2	-	20	-	-	18

Moreover, finding and implementing synergies between activities can be even more profitable, e.g., abandoned quarries that require filler material and industries generating inert waste (construction) or other activities requiring materials (road construction) [17,75,76]. Thus, even during restoration, an economic benefit is obtained from inert waste management. Sustainable management of extractive activity and its restoration, incorporating as much waste as possible, can contribute to the circular economy and achieve zero waste [77–79].

The restoration of mining areas requires not only technical capacity but also a binding regulatory framework. Ideally, restoration should be undertaken concurrently with extractive operations, insofar as this is feasible. However, in many countries where mining constitutes a major economic sector, this remains uncommon. The extensive legacy of abandoned unrestored sites has prompted several nations to develop action plans aimed at addressing mine rehabilitation [28]. The formulation of contingency plans for mine closure, explicitly incorporating post-restoration land use, could mitigate adverse impacts on neighbouring communities [55]. Yet, restoration efforts have traditionally prioritised environmental rehabilitation, often neglecting social and economic dimensions [49]. Regulatory frameworks should therefore incentivise environmental restoration as a prerequisite to broader socio-economic recovery.

Given the increasing use of mine residues and other industrial by-products in rehabilitation activities through the creation of technosols, there is a pressing need for clear legal provisions governing their use. Certain EU member states, such as Spain, have enacted legislation in this regard [80], and in some regions, more detailed regulations specify the physicochemical and microbiological requirements of materials employed in technosol formulation [81]. Nonetheless, in other jurisdictions, technosols are not formally recognised within national soil classification systems, which represents a further constraint to their effective deployment [36].

The first step for an adequate mining restoration begins with an exhaustive study of the geological, environmental, climatic, soil, hydrological, etc., characteristics. This is followed by the development of a planning and restoration project that includes biotechnology, objectives, indicators and measurement methodology to analyse the progress and success of the restoration in all areas of knowledge [28,36]. In general, the success of restoration is usually measured solely based on the density of vegetation cover and its degree of mimicry. The objectives of mine restoration should encompass erosional stability, the enhancement of biodiversity and ecosystem functionality, and the long-term monitoring of site conditions throughout the post-restoration use phase [49,61], in order to identify potential deviations and facilitate the continued adaptation of the environment to its designated function. The benefits of successful restoration, as we have indicated above, are even greater (not only in economic terms) if the subsequent benefits of both direct use (e.g., agro-livestock production, aquaculture, energy generation and storage, educational and species conservation activities, recreational and tourist activities) and indirect, population protection (e.g., flood control, storm buffering, carbon sequestration) are included. These future benefits should therefore be included in the net balance of a restoration, and a monitoring plan should be drawn up to verify that environmental, social and economic objectives have been achieved [20,82]. This study of pre-restoration conditions and the proper design of a restoration project is vital to avoid unforeseen costs [28].

However, there is a need for further research, development and application of new biotechnologies that can be more economically and technically efficient for each type of mine and climate conditions [28,83]. Technosols are a low-cost, functional and effective biotechnology for mine restoration [32,36,38]. The work of Robinson et al. [84] concluded that the raw material's cost to produce the topsoil (excluding transport, handling, application and the time required for soil development), using materials purchased in bulk in

the UK, was approximately 94,632 USD for 30 cm of topsoil per hectare. Using this data as a reference and based on the global surface area affected by mining activity as calculated by Maus et al. [3], the total cost of purchasing materials for topsoil recovery amounts to 829.711 billion euros. Therefore, utilising residues instead of buying raw materials to develop fertile soils (technosols) could save these costs [36]. Beyond economic savings, the repurposing of mine waste and organic residues from other industrial activities as backfill material or as constituents of technosols may substantially mitigate environmental impact. This approach obviates the need for soil extraction from undisturbed areas, thereby limiting the spatial extension of mining-related disturbances [34,83].

The expansion of knowledge regarding the formulation and application of technosols remains essential, and it should be systematically disseminated to stakeholders involved in regulatory frameworks, project design and assessment, restoration management, and long-term monitoring [36]. The integration of computational and geospatial technologies, such as geographic information systems (GIS), unmanned aerial vehicles (UAVs), and Earth observation tools, is likewise necessary to characterise the pre-existing site conditions, geomorphological and hydrological modelling, and evaluate restoration progress over extended temporal scales [28,85,86]. These technologies are fully compatible with technosol-based reclamation strategies, and they may facilitate the development of site-specific design plans tailored to the heterogeneous conditions within mining areas (e.g., contamination levels, pH constraints affecting biodiversity, surface water dynamics, slope stability). Although restoration monitoring should be conducted over broad temporal horizons, the restored ecosystem ought to be designed to achieve long-term self-sustainability [49].

As mentioned above, open-pit mines and waste rock dumps often create artificial landforms, like very steep slopes, that are highly susceptible to failures, landslides, rockfalls, erosion, floods, subsidence and sediment loss [44,55,87]. Conventional terracing and uniform grading often fail because they do not mimic the natural convex-concave profiles of stable hillslopes [55]. This leads to concentrated runoff, accelerated erosion, and, during severe storms, a high risk of failure [54,55]. A thorough geomorphological study, instead of terraced slopes, is the foundation of any successful mine restoration project [41,44]. This involves analysing the pre-mining topography, local climate, and hydrological regime to inform a “geomorphic landform design”. The prediction of geomorphological movements and ecological and natural disaster factors is crucial for avoiding unwanted consequences [28,50,51]. However, on occasions when it is not possible to act on the morphological design, and the restoration of slopes and esplanades must be faced, it is worth highlighting the following issues. The key factor for adequate mine reclamation in arid climates is the application of an adequate topsoil layer of fertile soil, irrespective of whether the slopes are linear or concave [55]. In cases where insufficient quantity or quality of fertile soil is available, concave rather than linear slopes should be chosen to reduce rill formation and sediment loss [55]. Technosols can help to reduce runoff on slopes if they are formulated with high organic matter content. Based on the fact that technosols with 15% compost content can have the same erodibility rate as natural soils in arid or semi-arid areas [87]. Erosion control blankets are also often incorporated into slopes, but although they achieve a high rate of soil erosion reduction, they are expensive [88,89]. The Jin and Englande [88] study concluded that the most cost-effective measure is temporary seeding with perennial rye grass. Posthumus et al. [89] tested that mulching is one of the measures with the best results in terms of erosion and economic return. Thus, by providing a technosol with high organic matter content, designed for the rapid growth of plant species capable of developing as deep, extensive and resilient root systems as possible, we can achieve erosion reduction cost-effectively.

The hydrogeological problems that can arise in a mining restoration, as discussed above, are complex to solve [44]. However, the best measure to take is preventive. This includes ensuring an adequate study of the water basin and defining a topography designed for proper water management [62]. In addition, mining waste (mainly rock) can help prevent problems on slopes due to water erosion. It is commonly used in breakwater walls at the base of slopes and in stream beds. However, more recently, they have been used to create drainage strips in restoration areas to protect the slope from runoff, with rapid benefits. In the restoration initiative undertaken at a disused clay quarry (Figure 6), coarse to medium-grade limestone waste was employed in the construction of the drainage strip [90]. Figure 6a shows the diagram of surface water circulation in the restored mine esplanade. The red arrows indicate the direction of movement of surface runoff towards the drainage strip. The blue line shows how the surface runoff water is collected and directed towards the canalisation parallel to a road, to prevent large volumes of water from reaching the slope (orange dashed line). This ensured the geotechnical stability of the slope and its water functionality, directing runoff and facilitating its infiltration into the subsoil [90]. In addition, it served as an area of rapid colonisation by plant species (Figure 6b), due to the accumulation of seeds, which further improved sediment retention and reduced water velocity, as well as helping to camouflage the drainage strip. The incorporation of technosols can reduce soil loss and erosion by promoting soil aggregate formation [91]. In fact, it has been shown that the pedogenesis of technosols is much faster than that of natural soil [92,93].



(**a**) (**b**)

Figure 6. Diagram of surface water circulation in the restored mine esplanade (**a**) and detail of the drainage strip with the presence of vegetation (**b**). (Alicante, Spain).

Although this issue has received comparatively limited scholarly attention, the application of technosols within aquatic mine environments warrants further consideration as it may raise specific environmental concerns. The development of a constructed wetland ecosystem with different types of technosols (hyperalkaline, hyper-reducing, anionic adsorbent and eutrophying) to treat hyperacid mine water was successfully developed and fully restored to drinking water quality [93,94]. The state of the aquatic ecosystem, which can be a neglected part of the restoration process, should be examined in more detail. Recent investigations have explored the potential for aquaculture development in flooded post-mining landscapes [74]. The accumulation of substantial water volumes in unrestored mine pits may increase the risk of flooding [95], while alterations in the quality of both surface and groundwater, within abandoned sites and adjacent areas have also been documented [94,95]. Fluvial systems are particularly susceptible to mining-

induced disturbances, which may exacerbate flood risk and facilitate the dispersion of pollutants [44]. Constructed wetlands, recognised for their capacity to purify contaminants, regulate hydrological regimes, and support biodiversity, represent a nature-based solution with considerable ecological value. Their implementation can be achieved at relatively low cost, particularly when locally available waste materials, such as technosols, are utilised [96]. Accordingly, the integration of wetland creation into mine restoration strategies, using tailored technosols, may contribute to risk mitigation and support the ecological rehabilitation and subsequent utilisation of degraded sites [93].

Moreover, mine restoration designs should take advantage of the presence of extractive waste and other materials available (demolition waste from mine construction) in pursuit of environmental and economic sustainability [97]. In mining, a significant portion of the extracted material is considered waste [98,99]. The percentage varies depending on the type of mine and the resource being extracted, but it is common for the waste to be a substantial majority of the mined material. For some metals, for every unit produced, there may be as little as 1% metal and greater than 99% tailings [44,94,100]. Backfilling of underground workings with rock waste or tailings from the mine itself is a common mitigation measure, but is not always feasible or effective, especially in abandoned mines where accurate maps of the workings may not be available [50,101–103]. It has been found that in some mine restorations where the base ecosystem is specific, such as gypsiferous, the use of mine waste as backfill material is a successful strategy [52,60]. The structural capacity of the backfill material is crucial here; a weak backfill may not be able to support the overlying rock, leading to delayed or localised subsidence. The risk of subsidence must be thoroughly assessed through geotechnical surveys and modelling to inform the restoration strategy and ensure public safety. Therefore, knowledge and study of the physico-chemical and geotechnical properties of mining waste and their associated risks (e.g., pollution potential, bearing capacity, water retention capacity) are increasingly required [16,38,104,105]. In addition, mine stone waste can be used to build technosols. The study by Rieder et al. [58] concluded that the most effective formulation for developing a vegetation community was 30 cm of waste rock amended with lime and mushroom compost and covered with 15 cm of limed, fertilised stockpiled topsoil. It was appropriate to use rocks discarded from the mine, even though they were acidic waste rock.

To replicate an ecosystem, we must first analyse the physico-chemical characteristics of the soil that supports it. In cases of shortage or lack of fertile soil, according to this information, and the phytochemical characteristics of the available residues, we can prescribe and formulate the required soils (technosols), minimising risks [23,38,106–108]. Not only do we reduce the risks by rigorously characterising the waste, but by incorporating it as a raw material in the restoration plan, we can narrow the environmental, social and economic risks associated with its accumulation in waste dumps or tailings ponds [36]. Problems of runoff erosion, poor drainage, inadequate water retention and lack of fertile soil can be addressed by incorporating residues with high organic matter content [36,58]. Solutions for soil problems in mine restoration focus on soil amendments, biological reintroduction, and soil engineering techniques (technosols). To address low fertility, it is essential to apply large quantities of organic matter, such as compost, agricultural or pruning residues, or manure, to enrich the soil with nutrients and improve its structure [38,106,107]. Nutrient-rich residues from other activities can be raw material for the formulation of technosols. In this way, we would enhance partnerships and provide the organic matter that is normally in short supply in mine reclamation [109]. Using slow-release biofertilisers and planting nitrogen-fixing legumes can also help increase long-term nutrient availability. Moreover, inadequate physicochemical properties require specific amendments: alkaline wastes can be applied to neutralise acidity and sulphur to reduce alkalinity [38,110,111]. Contamination

can be mitigated with phytoremediation or by using amendments that immobilise heavy metals [38,83,110]. Soil texture and structure are improved by adding sand, clay, or organic matter. However, the use of amendments or residues must also be performed with a prior study of their characteristics, as they may entail certain risks, such as the presence of trace elements, the rapid or slow release of nutrients not adjusted to the needs of the plants, as well as favouring the germination of rapidly colonising species that limit the development of native species [52,57,107,108].

To restore biodiversity and biological activity, it is critical to reintroduce soil microorganisms and fauna. In certain restoration contexts, evidence suggests that the incorporation of technosols enriched with organic matter may contribute more significantly to the recovery of soil microbial biomass than the mere establishment of tree cover [110]. Moreover, technosols can contain beneficial microorganisms or even be designed to incorporate necessary organisms such as nitrogen-fixing bacteria, ligninolytic fungi, which contribute to increasing the biodiversity pool [93]. Adding organic matter (technosols) like compost and wood mulch provides food and habitat for soil organisms, encouraging natural colonisation [110]. Fostering biological activity creates a positive feedback loop: organisms improve soil structure and nutrient availability, which in turn support plant growth, thereby enhancing organic matter availability, which in turn may facilitate increased colonisation by a broader range of organisms.

To mitigate the impact of severe climatic events, it is crucial to build soil resilience. Applying technosols protects the soil surface from heavy rains and winds. Growing a dense vegetative cover with deep-rooted species and establishing windbreaks with trees and shrubs can reduce wind erosion and stabilise the soil. Increasing the soil's organic matter content, with technosols, also improves its capacity to hold water and resist desiccation, making it more resilient to droughts [112]. The combination of these solutions creates a more stable and fertile soil, capable of sustaining a restored ecosystem in the long term. A holistic, geomorphology-based approach to mine restoration is essential for creating stable, functional, and self-sustaining landscapes. In severe climates, where water scarcity complicates plant survival, it is advisable to consider designs that allow greater water retention capacity, including the possibility of accumulating rainwater and dimensioning of water evacuation channels for extreme events of greater risk to stability [28,91,112]. The design must explicitly consider the site-specific geotechnical properties of the available materials in order to construct a landform capable of withstanding both surface and subsurface instabilities, not only under present conditions but also in ways that allow adaptation to the projected impacts of climate change.

Moreover, the choice of species for revegetation is also a key aspect, prioritising autochthonous species adapted to the environmental conditions [28,57]. Using a diversity of native plant species, including deep-rooted grasses and shrubs, it can improve soil stability and resistance to both drought and floods. The incorporation of flowering plants increases insect abundance and family richness, which helps natural pest control and enhances the development of ecosystem services associated with pollination [113]. However, plant mortality needs to be analysed on a long-term basis, although it is rarely studied on a long-term scale [64]. The success of plant survival and germination is also closely related to soil quality [58]. With the use of good-quality compost, a high germination rate (70%) is expected, but as the quality of the compost decreases, so does the germination rate [114,115]. Therefore, it is necessary to develop technosols with an adequate quality and organic matter content. Furthermore, they can be designed to meet the requirements and preferences of the plant species to be enhanced. The development of a plant community also leads to improvements in water quality both around the restoration and further away, reducing the off-site movement of sediment, acid runoff, and heavy metal content [58].

To control herbivory, individual plant guards can be used to shield seedlings [64,116]. However, the plant wards have certain limitations. The plastic ones increased the air temperature by an average of 6.7 °C, the light levels inside the shields were twice as low and sometimes are not sufficiently dissuasive [117]. Consequently, plastic protectors appear to be less suitable under Mediterranean climatic conditions, wherein shade-cloth tree guards are generally considered a more appropriate alternative [117]. Based on practical experience, it appears advisable to assess in advance whether the area targeted for restoration is situated within a zone characterised by a high density of herbivores. If it is not possible to control the population of the herbivore, it is only viable to study which plant species were most affected. The introduction of a diverse assemblage of plant species has revealed selective herbivory patterns, with rabbits exhibiting clear preferences for certain taxa. Consequently, subsequent planting efforts prioritised species less favoured by herbivores, particularly those already prevalent in the surrounding landscape. Moreover, high-density planting has been shown to enhance the likelihood of plant survival under sustained herbivory pressure [64,116]. Biological control, or the introduction of natural predators, can manage insect pests. For the introduction of endangered or non-commercial species, extensive research into their ecological requirements is required. Seeds should be collected from local populations, and seedlings should be raised in specialised nurseries before being planted. The soil must be amended to meet its specific physicochemical properties and nutrient needs. In terms of application in some particular ecosystems, for instance, to achieve a gypsiferous soil ecosystem, gypsum spoil can also be incorporated. In areas where a gypsiferous soil ecosystem is required, gypsum spoil can also be incorporated [57]. In these ecosystems, it is also favourable to introduce high-density vegetation [57]. Technosols can be designed to meet the characteristics of these specific substrates, which are vital for the development of the associated ecosystem.

Occasionally, the presence of endangered species that have grown spontaneously in postmining areas has been observed [118]. To maintain and protect unique species or ecosystems, the first step is a thorough site inventory to identify these elements. Buffer zones should then be created around these areas, and the restoration strategy must be adjusted to avoid disturbance. For the eradication of alien or invasive species, an aggressive control plan should be implemented before revegetation begins, and rapid incorporation of selected species can limit the development of invasive species during restoration [66]. Effective control of invasive or undesirable species constitutes a critical phase within the restoration process. The literature suggests that a comprehensive characterisation of waste materials utilised as backfill may be instrumental in promoting the establishment of introduced species, facilitating spontaneous colonisation, enhancing biodiversity, and improving slope stability [60]. One of the drawbacks is that plant communities may develop spontaneously that are not those of the reference ecosystem [61].

The lack of services (e.g., electricity, water) in remote restoration areas complicates restoration work. Even if planting or seeding is planned for times when rainfall is more likely, some irrigation may be required [28]. Transporting large volumes of water to remote sites is often impractical. An additional logistical problem is where and how to store the seedlings to be planted when the work is spread over several days, to ensure their survival and avoid vandalism. Successful mine restoration often requires a high level of inter-organisational collaboration, which can be a significant logistical hurdle. Securing co-operation with neighbouring communities and landowners is essential for access, land use agreements, and community support, but can be complicated by historical tensions [23,61]. Furthermore, establishing partnerships with research centres and universities is crucial for accessing scientific expertise on soil science, plant species selection, and monitoring; however, such collaborations often exhibit protracted formalisation processes and necessitate

sustained managerial oversight. Coordinating with multiple stakeholders, from government agencies to local groups, is a time-consuming and complex task. For infrastructure and equipment, a detailed site assessment should be conducted to plan for all necessary infrastructure from the start. This can include building temporary access roads, setting up on-site power generators, and securing all machinery well in advance. Sourcing equipment locally, when possible, can reduce transportation costs and maintenance challenges. To mitigate the risk of vandalism to equipment and materials, overnight accommodation is frequently arranged in nearby locations where enhanced surveillance can be maintained, particularly given the often remote siting of quarries and mines. The need for constant security patrols or the installation of monitoring systems adds to the operational burden [61]. To manage the presence of passers-by, clear communication and designated public access are key. Installing visible signage and erecting secure fencing around sensitive restoration areas can inform and guide visitors [61]. In some cases, creating and maintaining separate, safe pathways for public use can redirect foot traffic away from fragile areas, while still allowing the community to engage with the site.

In any case, the development of a standardised methodology for defining appropriate indicators would be valuable in assessing the progression of restoration processes and in determining the stage at which restoration outcomes may be regarded as successful. Furthermore, such methodologies ought to be adapted to the specific type of restoration undertaken, the biotechnological approaches employed, and the prevailing climatic conditions. Moreover, this methodology should include the valuation, including monetary valuation, of the social, environmental and economic values recovered after restoration.

6. Conclusions

The increase in demand for non-renewable resources will lead to a rise in mining activity and, consequently, in the number and size of mines that will need to be rehabilitated. This is in addition to the vast number of abandoned mines already existing worldwide.

Mine restoration is confronted with a set of multifaceted challenges, most notably the substantial volumes of waste generated and the limited availability of fertile soil. It can also highlight other problems that are not addressed as frequently in the literature, but are also common (herbivory, vandalism, consequences of climate change, logistical challenges, overbooked situations and problems of large esplanades). The key factor for successful mine restoration in arid and semi-arid climates is the availability of fertile soil in quantity and quality. All these issues, combined with the fact that some countries lack a legal framework that mandates restoration, and the high costs associated with restoration, lead to the abandonment of mines without restoration, which exacerbates environmental, social, and economic problems.

Accordingly, the formulation of technosols from waste materials is increasingly recognised as a holistic approach to addressing complex environmental challenges, including the enhancement of soil fertility, reduction in erosion, improvement of water retention, and restoration of biological activity. Moreover, technosols not only demonstrate technical efficacy but are also associated with notable economic and social advantages. A key consideration highlighted in the literature is their capacity to significantly reduce costs relative to the use of commercially sourced soil-building materials, while simultaneously advancing circular economy principles and zero-waste objectives. The inherent versatility of their design may further facilitate adaptation to the heterogeneous ecological conditions and functional demands characteristic of large-scale mining landscapes.

Technosols promote broader socio-economic and climate change resilience. Technosol application enables the design of restored areas for diverse post-restoration uses, thereby generating significant environmental, social, and economic benefits, such as flood control,

carbon sequestration, agroforestry, and recreational activities. This integrative perspective, which incorporates design considerations for future land use, constitutes a central contribution of the present study. Finally, further research is warranted, alongside the development of a practical guide for restoration managers and the systematic transfer of knowledge to all stakeholders involved in the reclamation process, in order to optimise and expand the implementation of technosols.

Author Contributions: Conceptualisation, M.B.A.-C. and J.N.-P.; methodology, M.B.A.-C. and J.N.-P.; validation, T.R.-E., A.P.-G., M.B.A.-C. and G.G.-F.; formal analysis, M.B.A.-C. and G.G.-F.; investigation, T.R.-E., A.P.-G. and M.B.A.-C.; resources, T.R.-E., A.P.-G. and M.B.A.-C.; data curation, M.B.A.-C.; writing—original draft preparation, T.R.-E., A.P.-G., M.B.A.-C. and J.N.-P.; writing—review and editing, J.N.-P. and G.G.-F.; supervision, M.B.A.-C. and J.N.-P.; project administration, J.N.-P.; funding acquisition, J.N.-P. and G.G.-F. All authors have read and agreed to the published version of the manuscript.

Funding: The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: this research, funded by the State Research Agency (AEI) of the Spanish Ministry of Science and Innovation (MCIN) (MCIN/AEI/10.13039/501100011033), was made possible by Grant PID2021-128961OB-I00 from FEDER funds.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: Authors thank the State Research Agency (AEI) of the Spanish Ministry of Science and Innovation (MCIN).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviation

The following abbreviations are used in this manuscript:

GIS	Geographic Information System

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