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Review

Bringing Life Back into Former Mining Sites: A Mini-Review on Soil Remediation Using Organic Amendments

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Abstract: Former mining sites cause serious environmental problems worldwide as they are contaminated with hazardous levels of metals. Mined lands are characterized by a deserted landscape due to the lack of organic matter in soil. Research analyses confirmed that the structure of soil in abandoned surface mines has affected the occurrence of ecological processes and natural colonization of vegetation cannot take place. Moreover, phytoextraction of metals is possible only in soils with specific parameters. Previously conducted studies proposed the in situ supplementation with biochar, compost or agri-food wastes as a solution to the lack of organic carbon and nitrogen in areas affected by mining. Therefore, the main aim of this review is to investigate what improvements different organic amendments can bring to mining-impacted soils to support plant growth without affecting the bioavailability of metals. We concluded that contaminants are specific to the mining activity, while organic treatments cause the increase of soil pH, which influences, to the greatest extent, the bioavailability of metals.

Keywords: soil remediation; technosols; abandoned mining sites; mine tailings; organic amendments; soil contamination; mining activities

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1. Introduction

One third of the soil resources worldwide are moderately or severely depleted [1]. The degradation of soil can occur naturally through erosion, which is induced by the force of wind or movement of water. However, this geological process is enhanced significantly by the unsustainable management of soil resources [2]. The natural landscape faces a continuous transformation determined by human activities. Soil quality declining is among the side effects of urbanization [3], deforestation [4] and mining [5]. Additionally, waste pollution in certain areas has reached high levels hence the negative effect on soil health [6].

Mining negatively impacts soil structure in several ways; the underground ore extraction leads to the subsidence of land [7]. Therefore, vertical leakage of nutrients and impairment of the soil microbial community occur [8]. The open-pit mining is more harmful as the vegetation and soil from the surface is relocated, leaving behind a barren land. Moreover, mining waste which is deposited in tailing ponds and dumps can cause heavy metal pollution. Mining wastes pose serious threats to environmental and human health via the contamination of soil and water with toxic metals [9–11]. These are mobilized through the acid mine drainage formed because of the contact between water and sulfur-bearing minerals [12,13].

Soils in former mining areas can be declared technosols as their structure is seriously changed by human activity (Figure 1). They are usually characterized by increased concentrations of heavy metals and nutrient depletion, hence the incapacity of vegetation to survive [14]. Therefore, the ecological restoration of former mining sites represents a difficult achievement. Plant colonization of former surface mines can occur naturally [15,16]. Recent evidence shows that the process may take more than seven decades after the closure of mining activity [17].

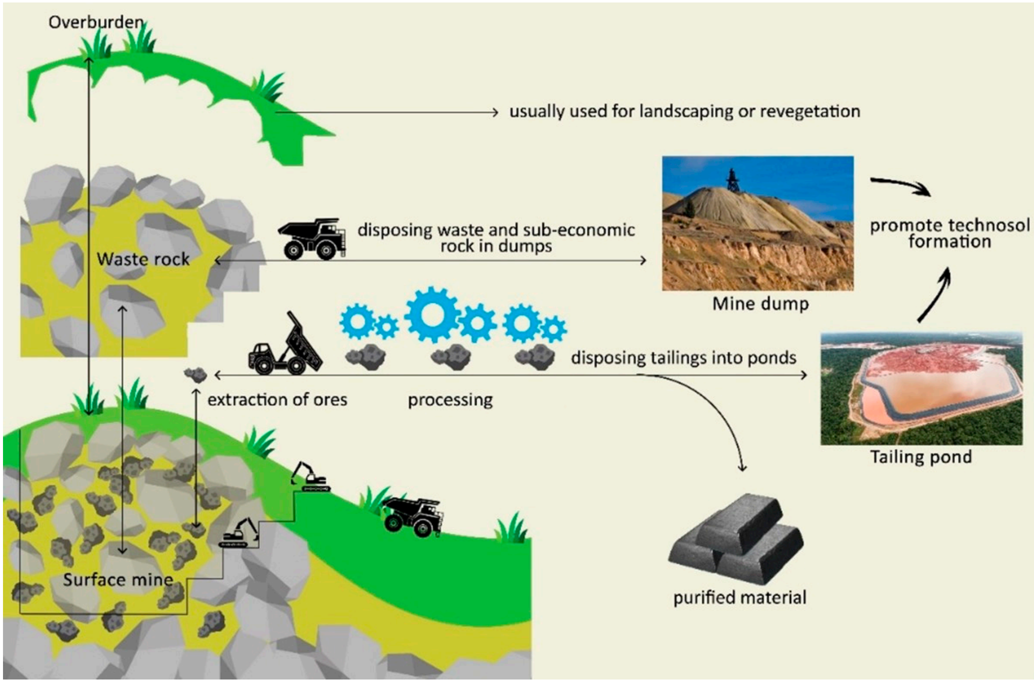

Figure 1. Mine waste promotes the generation of technosols (done by the authors).

Analyzing the above, it can be noted that soil degradation caused by mining is a topical issue. Previous studies proposed the use of different organic amendments to support and accelerate the remediation and rehabilitation of lands affected by mining. Biochar [18], manure [19], agri-wastes [20] and compost [21] could act as important sources of nutrients. Additionally, the involvement of plants can be useful in the immobilization or removal of contaminants [22].

The purpose of this review is to discuss the suitability of organic treatment in enhancing the fertility of soils in former mining areas. To achieve our main aim, we established the following objectives: (i) to provide insight into the physical and chemical parameters that manage the ecological incompatibility of mining-affected soils and (ii) to investigate the influence of in situ organic supplementation on them.

2. Mining-Economic Gain versus Environmental Issues

Mining is an important economic sector that supports the development and digitalizing of modern society. Whether we consider fossil fuels, building materials or high-tech metals, mining contributes to the global economy by extracting several valuable resources. A report from International Council on Mining and Metals showed that revenues obtained from mining considerably support the economy of underdeveloped countries [23].

More than 57,000 km^2 of our planet is occupied by current and former mining sites and facilities. Fifty-one percent of these areas are spread throughout the territories of China, United States, Russia, Australia and Chile [24]. In the United States of America, the production of mines is estimated at USD 80 billion [25]. The mining industry in the European Union comprises almost 17,000 businesses and 392,000 employees. The total added value produced by EU mines was EUR 33.1 billion in 2019 [26].

Besides surface and underground extraction, placer and in situ mining are among the main mining techniques implemented nowadays. Placer mining is useful when minerals from aquatic sediments are exploited, while in situ leaching (ISL) is mainly used for the recovery of uranium [27,28], as well as for other metals such as copper [29] or gold [30]. ISL exploits the geology of porous orebodies by dissolving ore in an acid or alkaline solution, which is then pumped to the surface where the mineral is recovered from the aqueous solution [31]. Mining is a high waste generator regardless of the method considered. Mine waste consists of huge amounts of soil and unvaluable rocks with traces of minerals. These cannot be extracted conventionally because of technological limitations or unfeasible costs [32]. Solid waste from mineral extraction is stored in dumps. However, liquid tailings and slurry are produced in early steps of ore processing. These are stored in ponds obtained via the construction of large dams [33].

The natural landscape has suffered severe transformation because of mining operations (Figure 2). Deforestation of large surfaces was implemented to make room for quarries and surface mines [34]. Moreover, dust, emissions and metal-rich waste has given mines the status of major polluters; thus, the occurrence of ecological imbalance [35–37] and increase in respiratory diseases in mining areas is of little surprise [38,39].

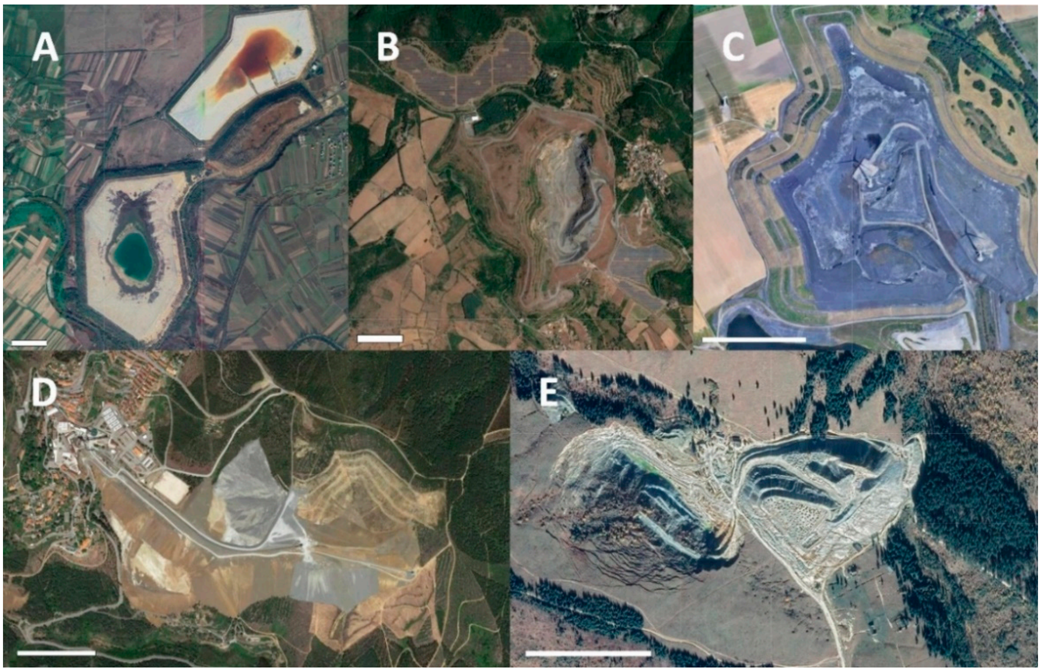

Figure 2. Influence of mining activities on natural landscapes. Illustrated mining sites are located (**A**) in proximity to Baia Mare (Romania); (**B**) near Villaniere and Salsigne (France); (**C**) near Kamp-Lintfort (Germany); (**D**) Panasquiera Mine, Barroca Grande (Portugal); (**E**) Rodnei Mountains, Suceava county (Romania). Identification of mining sites and visualization of images were done using the data set developed by Maus et al. [24] available on FINEPRINT Geovisualisations database. Scale bar: 300 m.

Between 2005 and 2015, Brazil's Amazon Forest lost 11,670 km^2 because of the expansion of mining and its supportive infrastructure [40]. Columbian forests have reduced by over 4000 km^2 because of illegal mining activities in the past 18 years [41]. Tropical forests in South America are at risk because of the expansion of gold mining that satisfy the global growing demand [42]. The increase of illegal mining is also worrying because of difficulties in controlling and monitoring it. The world's second largest rainforest located in the river Congo Basin has also been affected by mining-driven deforestation, but to a lesser degree. However, the establishment of surface mines in Africa resulted in a substantial loss of farmland, causing the relocation of farms into forested areas [43].

3. Abandoned Mines Have the Potential to Be Converted into Valuable Infrastructures

In the near future, the mining industry would probably face difficulties in complying with the international agendas encouraging environmental conservation policies, given the increased expected demand for minerals [44,45]. Additionally, the depletion of minerals in some areas has led to the abandonment of mines. Australia hosts nearly 50,000 former mines, while Canada has about 10,000. Additionally, nearly 5400 mines in China are depleted [46].

There are some ways in which former mining sites can be reutilized. One of the oldest ideas of putting depleted underground mines to use is mushroom farming [47]. In such cases, the organic substrate could be represented by wood chips and sawdust, which are commonly used as growing media for mushrooms [48]. Mines might also be dedicated to different types of subsistence agriculture in the case of a global catastrophe [49]. Moreover, mine-polluted lands, which are amended with organic matter for enhanced fertility, could be useful for the cultivation of crops intended for biodiesel production [50].

Currently, a lot of former mines are repurposed for cultural, recreational and commercial activities. According to Kivinen [51], abandoned mining sites and facilities from Finland hosted concerts, golf courses or motorsport and off-road driving events. Museums and industrial facilities including factories, offices and warehouses were established in other former mines in the same country. Additionally, military facilities and exercises were organized in such areas [51].

Companies from Central Europe intend to use geothermal mine water for energy purposes, including the generation of electricity and heating of houses [52]. On an abandoned surface mine in Germany, solar panels were installed. Nowadays, the facility produces 166 MW of electricity [53]. Other green infrastructure including wind turbines and solar panel farms built on lands affected by mining can be observed in the FINEPRINT Geovisualisations database (Figure 2B,C).

4. Physicochemical Characteristics of Technosols from Abandoned Mining Sites

Soil quality is measured through physical and chemical indicators. A significant role in the selection of these parameters is played by their variability in time and level of stability. The stability levels of soil parameters can be distinguished as follows: stable, also known as "inherent" (soil depth and granularity); relatively stable (metals and organic mass content); relatively dynamic (nutrient content and pH); and dynamic (humidity, temperature, microbiota and enzymatic activity) [54]. As soil quality cannot be determined by simply measuring crop yield or other single indicators, and although patterns are helpful, some findings cannot be linked to other research due to the different soil-ecological conditions in which they were obtained [55]. Therefore, the quality of soil remains dependent on and is reflected by the assessment of multiple physicochemical indicators that reveal how soil performs all of its function in present and for future use.

International Union of Soil Sciences has recently introduced technosols in the World Reference Base for Soil Resources, an international classification system. Technosols are soils with a structure that is highly impacted by anthropic activity. The existence of artefacts, which can be liquid or solid substances, is a characteristic of technosols. Artefacts are artificial in nature, being derived from industrial processes and placed in natural areas. Industrial waste, oil products, mine spoil, crushed stone and garbage are some examples of artefacts [56].

Technosols are formed usually in urban and industrial environments. Soils from mining areas are considered technosols because of their composition in minerals extracted from greater depths. Wastes from mining are also included in technosols. The physicochemical parameters of soils in areas where the mining industry operated are significantly different from agricultural or ecological ones and may vary in accordance with the specifics of the mining operation (Table 1). In coal mine areas, concentrations of organic carbon, available nitrogen, available phosphorus and available potassium have been found to be low as compared to normal soils [57]. The same trend was seen in heavy metal mines where the organic carbon and total nitrogen concentrations were lower compared to those from unaffected areas. However, one or more of the mined products were detected in higher concentrations [58]. In areas of arsenic and lead mining operations, a strong negative relationship was observed among the biological activity of different soil enzymes and arsenic contamination [59].

Table 1. Physicochemical properties of technosols from different abandoned mining sites.

Location	pH	TOC [1]/DOC [2]	Total N	Main Contaminant	Other Contaminants	Reference
Mining district La Unión (Spain)	3.2	0.5 g per kg	0.2 g per kg	Zn (1.570 g per kg)Pb (1.225 g per kg	Al, As, Cd, Co, Cr, Cu, Mn, Ni, Sb, Se,	[60]
Former gold mine La Petite Faye (France)	5.94	21.6 mg per L	not determined	As (15.7 mg per L)	Pb, Sb	[61]
Former copper mine Touro (Spain)	2.73	1.93 g per kg	undetectable level	Cu (0.637 gr per kg)	Fe, Mn, Pb, Ni, Zn	[62]

[1] TOC: total organic carbon; [2] DOC: dissolved organic carbon.

Arsenic and lead prevail in technosols from gold mining sites. For example, the arsenic level in soil from La Petite Faye mine (France) was 24 times higher than in normal soil [61]. Zinc, mangan and iron are also among the metallic elements included in technosols. In a mining district in Spain, soil pH was near 3 and the organic carbon and nitrogen quantity was less than 0.5 g kg^{-1} [60].

Underground mining operations are causing drastic disturbances to soil nutrients. Soil organic mass (SOM) in mining sites have a considerable variation in spatial distribution at different soil depths [63,64]. Significant differences were also observed between the SOM in the pre-mining and post-mining soil, as mining disturbance caused the loss of the litter layer and microbiota, which affected the availability of the soil nutrient-holding capacity in the topsoil [65].

In terms of pH, contamination with metals gives technosols from mining areas an acidic nature. Additionally, the organic carbon and nutrient content are poor in mine technosols hence the lack of impact of vegetation and soil microbiota. Mining waste deposited on the surface is characterized by low nutritionally availability and consequently generate nutritionally deprived habitats with alteration of pH values [66].

Soil pH is controlled by the leaching of cations such as Mg, Ca, K and Na, allowing H^+ and Al^{3+} ions to dominate exchangeable cations. Except from highly acidic or alkaline soils, the major exchangeable cations are in typical proportions of: 80% Ca^{2+}, 15% Mg^{2+}, 5% K^+ and Na^+. Depending on the extent of the microbial flora, small variable amounts of NH^{4+} can substitute any of these cations [67].

Low soil pH in mining areas is most commonly due to sulfide minerals that get in contact with water and air, producing sulfuric acid. This can also result in acid mine drainage (AMD) which is the movement of highly acidic water formed through the chemical reaction of surface water (i.e., rainwater) and shallow subsurface water with rocks that contain sulfur-bearing minerals, resulting in sulfuric acid. In contrast, net alkaline mine drainage (NAMD) occurs when calcite or dolomite is present [68].

According to Rieuwerts et al. [69], several factors such as cation competition, microbial activity and temperature influence soil metal bioavailability, but these appear to play a minor role when compared to the effects of pH, which facilitates the absorption of heavy metals by plants and other organisms due to the fact that the solubility of metals increases at low pH values and decreases at high pH values. In a recent paper surveying a region of Zn-Pb ore mining and processing industry, soil acidification was observed to cause a significant increase in metal mobility in the following order: Cd > Zn > Pb, compared to samples from an unpolluted area [70].

Metal bioavailability is highly dependent on pH. Nutrient availability is not determined only by pH; soil microbial communities play a crucial role as well [71]. However, pH is one of the most important parameters that control the change of the chemical forms of the elements, as well as the biology and biological processes of the soil [72].

5. Improvement of Soil Parameters in Mining Sites Using Organic Amendments and Soil-Remediation Plants

Flora and fauna are completely removed from mining sites during the displacement of soil. As a result, the fertility of soils in mining districts is negatively affected because of organic matter scarcity. The hydrological system may also be threatened by the mobilization of contaminants originated in mining activities [73].

Human intervention is necessary in order to enhance and speed up the remediation of these polluted areas. The concept of bioremediation consists of the use of bacteria, fungi and/or plants to immobilize or reduce pollutants from soil and water. Bioremediation relies on natural processes that aim to convert contaminated environment into a non-toxic one [74]. Different species were involved in the bioremediation of mining-affected soils. For example, bioremediation with *Pleurotus ostreatus* fungus was successfully performed in the removal and recovery of Mn^{2+}; Fe^{3+}; and Cd^{2+} from mine dumps [75]. Moreover, the bacterial strain *Pseudomonas stutzeri* was able to bioremediate a copper contaminated soil [76], while *Solanum nigrum* plant and *Mucor circinelloides* fungus were synergistically utilized for the removal of lead from mine tailings [77].

Different types of in situ bioremediation techniques were developed [78]. Phytoremediation was used mainly for the removal of pesticides and heavy metals [79], while biosparging was effective in remediation of oil derivatives from soil [80]. Biosparging uses the ability of aerobic bacteria to degrade mineral oils. The development and metabolic activity of these microorganisms at depth is supported by air injection into the ground [80].

Bioaugmentation uses selected or genetically modified microbial strains to enrich the native soil microbiota. This technique is useful when the autochthonous microbial population from the contaminated site is unable to act against pollutants [81]. In other cases, native microorganisms are metabolically adapted to the polluted environment, but for the effective remediation of the contaminant their growth need to be stimulated. Biostimulation usually involves the injection of nutrients such as nitrogen and phosphorus, as well as water, oxygen and oxidizing agents into the ground [82].

Supplementation of soil with organic amendments may be the simplest solution to re-establish the fertility of soils in mining districts, promoting the growth of microorganisms and plants. These act as organic matter suppliers and can raise the pH. There are different mechanisms by which organic amendments impact the contaminants in mined-affected soils. For example, the surface of biochar particles is negatively charged facilitating the electrostatic interaction between soil particles and metal cations [83]. Additionally, biochar has a high cation exchange capacity that increases its ability to adsorb metal ions [84].

The complexation mechanism could explain the remediation effect of compost and different organic wastes. These contain a large amount of hydroxyl- and carboxyl-containing molecules (e.g., humus substances) that interact with metal ions leading to the formation of stable complexes [85]. Not least, several studies showed that biomolecules can act as metal ion reducers, leading to the formation of less toxic zero-valent metallic particles [86,87]. Compost is also a source of microorganisms with biosorption and biomineralization potential. In a recent study, Vargas-Garcia et al. showed that *Penicillium chrysogenum*, *Fusarium solani* and *Graphium putredinis* isolated from compost have successfully accumulated lead from an in vitro medium. The compost was processed from sewage sludge, horticultural and municipal solid waste [88].

Some initiatives using organic amendments and soil-remediation plants were conducted in abandoned mining areas worldwide (Table 2). La Petite Faye is the name of an abandoned gold mine located in Massif Central region (France). In total, 12,000 m^2 of the surrounding land are covered with more than 30,000 t of waste produced by this mine until its closure. The level of As, Pb and Sb in the technosol formed near La Petite Faye is concerning. However, a recent study showed that supplementation of these technosol with 5% biochar can increase their ability to retain water by 16% and slightly increase the pH. The addition of biochar was also effective in restoring the total organic content. After the treatment, TOC in mine technosol was similar with a garden soil used as reference [61].

Table 2. Initiatives involving organic amendments and phytoremediation on soils affected by mining.

Location	Organic Supplementation	Soil-Remediation Plant Species	Reference
tailing pond in Cartagena-La Unión, Spain	raw pig slurry; pig manure; pyrogenic carbonaceous material marble waste ($CaCO_3$)	-	[60]
ruhanga tantalum mine in Gatumba Mining District, Rwanda	fresh farmyard manure	-	[89]
gold mine La Petite Faye in Limoges, France	garden soil Biochar	*Phaseolus vulgaris*	[61]
abandoned silver-lead mine in Pontgibaud, France	compost biochar	*Oxalis pes-caprae*	[18]
	compost hardwood-derived biochar	*Trifolium repens*	[90]
iron mine Joda East in Odisha, India	-	*Chrysopogon zizaniodes*	[91]
iron mine tailings in Mariana region, Brazil	vermicompost	*Zea mays* *Pennisetum glaucum* *Sorghum bicolor*	[21]
abandoned mining site in Touro, Spain	biochar derived from *Quercus ilex* wood ash and wastes from an aluminum company	*Brassica juncea*	[62]
manganese slag from Xiangtan, Hunan, China	spent mushroom compost	*Paulownia fortunei*	[92]
surroundings of Seosung mine, Seosan-si, Chungcheognam-do, Korea	eggshell rapeseed residue	-	[93]

Infertile soils rich in As and Pb also exist in Pontgribaud mining district in France. Here, a silver-lead mine functioned until 1947. The capacity of the surrounding soils to hold water was assessed at 30%. The addition of small fractions of biochar and compost had a beneficial effect on water holding capacity, raising it with 15%. However, these treatments have no impact on the bio-accessibility of toxic metals. Results showed that arsenic can be immobilized by the supplementation of soil with iron grit. Even though a solution for immobilizing lead was not discovered, researchers reported that these amendments increased the accessibility of technosol. The development of a clover (*Trifolium repens*) cover was achieved in the newly created technosol [90].

Large areas of land were negatively affected in November 2015 by the rupture of a tailing dam in Mariana region (Brazil). As a result, 39 million m^3 of iron-mine wastes spilled into the surrounding environment, reaching the Doce river basin. Level of Mn and Cr in soil exceeded the threshold. High content of iron was also confirmed. Esteves et al. [21] suggested a successful remediation of these lands can be achieved by supplementation of soils with vermicompost. Analyses revealed that soil pH in Mariana region is still suitable for plant growing, but the ecological disaster affected the organic matter and micronutrients contents. Micronutrients content in root and shoot of maize, millet and sorghum grown in the contaminated soil increased when vermicompost was applied. Moreover, no accumulation of lead, arsenic, iron or nickel in plants' tissues was observed. However, plants' roots were contaminated with chromium even after the supplementation with vermicompost [21].

Soils in the proximity of the abandoned Touro copper mine (Spain) contain large amounts of Cu and Zn. Their pH is also strongly acidic [20]. Forján et al. [62] found that biochar can increase the pH and carbon content of these soils. The effect of biochar was enhanced when a technosol containing 60% plant wastes and 10% agri-food wastes was added. Study showed that *Brassica juncea* can grow on the treated tailings and highlighted the important role of biochar in preventing the leaching of nitrates [62]. In addition, *Salvia* *verbenaca* plants can accumulate Cu and Zn from Touro mine soil in their roots. However, results suggested that supplementation with agri-food wastes and a nutrient rich mixture (containing wood residue, ashes, sewage sludge and mussel shells) have no impact on plant's capacity to bioaccumulate metals [20].

The in situ coverage of Touro mine soil with a 5 cm thick layer of organic waste led to the increase of pH up to an alkaline level, this resulted in the occurring of the natural colonization of the autochthonous plants. The organic mixture used consisted of mussels and eucalyptus wood residues that led to the development of Conyza (*Erigeron anadensis*) and Alfalfa (*Medicago sativa*) [94].

6. Conclusions

Former mining districts occupy important surfaces and are a source of hazards worldwide. More attention to post-mining remediation strategies is needed in order to reduce the negative impact of the mining industry and take advantage of these deserted places.

We observed that there is a lack of organic carbon and nitrogen in all mining-affected soils. Moreover, a dependence between the main soil contaminant and the nature of mining activities resulted from the study. The lack of organic matter is the main impediment of the natural colonization with native plants.

Revegetation is important as it can drive the removal of metals from soils, especially when soil-remediation plant species are involved. From our literature investigation, it turned out that the bioavailability of metal contaminants is mainly influenced by soil pH. Solubility of metals is inversely proportional with soil pH. Therefore, the accumulation of metals by plants is more efficient in acidic environments. However, an extremely low pH inhibits the growth of vegetation. From the above, we concluded that the optimization of pH is necessary to allow the development of plants without immobilizing metals into soil.

Our study concluded that supplementation with organic wastes can support plant growth in mine tailings by increasing the pH and organic matter content. Organic treatments are a simple and efficient solution for the initiation of soil ecological processes and revegetation.

Future in situ research should consider the uniqueness of technosols formed in different abandoned mining areas to find the most suitable treatments for their needs. Moreover, mines are usually established in places that are hard to access. Therefore, future studies may search for sources of organic matter resulting from local economies in order to facilitate the ecological restoration and prevent the high transport costs.

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