Environ Geochem Health (2023) 45:7459–7490
https://doi.org/10.1007/s10653-023-01700-x

REVIEW PAPER

An overview of the impacts of coal mining and processing on soil: assessment, monitoring, and challenges in the Czech Republic

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Received: 27 May 2023 / Accepted: 17 July 2023 / Published online: 27 July 2023

Abstract Coal mining activities are causing an extensive range of environmental issues at both operating and abandoned mine sites. It is one of the most environmentally destructive practices, with the capability to eliminate fauna and flora, impact the groundwater system, and pollute the soil, air, and water. The Czech Republic relies almost exclusively on coal as its primary domestic source of energy. The combined reserves of hard and brown coals in this country are 705 million tons. About 50 million tons of coal is produced annually, making it the 14th biggest producer in the world. Soil degradation is an inevitable outcome of the coal production from surface coal mining procedures in the Czech Republic. Significant changes have taken place in soil productivity, hydraulic characteristics, horizon, and texture as a result of soil pollution, bioturbation, compaction, and weathering. The current review has evaluated the impact of reclamation and coal mining on soil characteristics, including biological, chemical, and physical properties. Additionally, the study has outlined the process of soil formation in reclamation areas in the Czech Republic. In nutshell, research gaps and future directions in understanding coal mining areas and their influences on soils in the Czech Republic are identified.

Keywords Coal mining · Soil pollution · Heavy metals · Land reclamation · Czech Republic

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Introduction

Energy is the lifeblood of economies. Coal, petroleum, and natural gas are examples of energy-rich natural resources on which most of the countries rely (Jiskani et al., 2022). Coal has been mined continuously from ancient times since it is the most abundant fossil fuel on the planet (Niu et al., 2017). Coal is the most well-known primary energy source, accounting for more than 41.1% of global electrical output (Habib et al., 2019). With the tremendous advancements in the last century, it has been one of the primary driving elements in the industrialization and economic development of societies (Ge & Lei, 2013). In the Czech Republic's industrial growth as well as its previous and present energy mix, coal has played an essential role (Kavina et al., 2009; Vlček & Černoch, 2012). Due to the rising demand for energy, many developed and developing nations have boosted their coal mining production (Khan et al., 2018; Ozden et al., 2018). However, coal mining poses a significant threat to the surrounding environment through its detrimental impact on land surface, ecosystem and biodiversity destruction, exacerbation of soil erosion, and contribution to environmental contamination (Byrne et al., 2017; Pei et al., 2017).

Coal is a fuel with a very complicated chemical composition that consists of a mixture of carbon, hydrogen, sulfur, oxygen, and nitrogen that is related to other rock components and inorganic minerals. It is also one of the main sources of hydrocarbons in nature. Coal extraction and combustion are potentially detrimental processes that can emit significant amounts of ash and pollutants into the environment (Gopinathan et al., 2022a, 2022b; Lelieveld et al., 2019). In the coal mining process, elemental pollution is one of the most important environmental issues (Mileusnic et al., 2014). During the process of opencast and underground coal mining, various types of rocks and rock dusts with varied compositions are subjected to atmospheres and engage in accelerated weathering (Bhuiyan et al., 2010). Due to the great metal-scavenging capability of soils, they are typically considered as the ultimate sink for heavy metals emitted into the environment (Rouhani et al., 2023a; Tomiyama et al., 2020). The presence of an excessive quantity of pollutants can lead to degradation in the soil quality, which then poses a potential risk to human and animal health. This risk may arise either through direct contact or indirectly via the food chain (Kamanzi et al., 2023; Rouhani et al., 2022; Wuana et al., 2011).

Another environmental issue associated with coal mining is polycyclic aromatic hydrocarbons (PAHs). Hydrocarbons with two or more benzene rings are among these persistent organic contaminants. They are widely distributed everywhere from water and air to soil and sediment (Ambade & Sethi, 2021; Qin et al., 2014). PAHs have attracted global attention due to their potential for causing cancer, birth defects, genetic mutations, and adverse effects to both environment and the human health (Li et al., 2017). Consequently, the Environmental Protection Agency (EPA) in the USA has identified PAHs as a pollutant of high priority. Evaluating the concentration of these pollutants in soils is necessary since more people are exposed to PAHs (e.g., benzo(a)pyrene, benzo(b)fluoranthene, pyrene, chrysene, fluoranthene, phenanthrene, fluorene) through soils than through air or water (Fan et al., 2013; Padula et al., 2015).

Opencast coal mining operations generate significant quantities of solid waste materials, including stripped soils, coal gangue, and tailings, which require reclamation actions. In contrast to natural land, reclaimed land is typically prone to reconstruction due to its poor soil structure, high bulk density, and low levels of biomass productivity, structural stability, pH, available nutrients, and water-holding capacity. As a result, such land is often classified as degraded (Asensio et al., 2013; Shrestha & Lal, 2006). The altered topography and soil composition of reclaimed lands led to significant modifications to water and solute transportation within the soil (Ma & Zhang, 2016; Rodriguez-Liebana et al., 2014). Soils from mining areas are consistently identified as containing a coarser texture, a poorer structure, and a larger amount of rock fragments as compared to natural soils (Bussler et al., 1984). According to a study by Zhen et al. (2015), the solute transfer factors were varied and highly impacted by soil texture and bulk density. Furthermore, in columns of reclaimed mine soil, there has been preferential flow and transportation.

Motivated by environmental concerns, the Czech Republic (CZ) has implemented distinctive policies aimed at restricting coal mining for the past 28 years. In order to make it clearly evident where open-pit coal mining is allowed and where it is forbidden, the country implemented territorial mining limitations in 1991 (Rečka & Ščasný, 2017). The restrictions forced companies to reconsider their policies from investing in the coal industry using restricting mining activities to boundaries that have been considerably smaller than the country's real coal deposits (Sivek et al., 2017; Vlček & Jirušek, 2015). However, the mining activities outside those boundaries have never been formally shut down, and the restrictions have only been formalized through an executive order. Revising the restrictions has been a point of contention for various economic and political motives since they are only taken into account by the government that is in power at any particular time. Since the restrictions were established, interest groups have mostly engaged every administration, forcing them to reevaluate and ultimately reaffirm the limits. Because of such reoccurring issue of sustaining formerly adopted coal-restricting regulations, the Czech instance distinguishes between other coal-dependent nations that have attempted to limit coal usage (Lehotský et al., 2019).

This paper provides a comprehensive overview of the historical and contemporary advancements in comprehending the coal mining impact on soil quality, the potential hazards associated with coal mining, the influence of land reclamation on soil characteristics, and the practical implications of this knowledge on the affected soils in the Czech Republic. In addition to this, the most important mines in the history of mining in the Czech Republic as well as the environmental features of each site are discussed. To evaluate soil quality, contamination, and the toxicological impacts of contaminants from mining sites, an in-depth summary of earlier studies and monitoring investigations is provided and the most significant results are presented. In addition, research gaps and future directions in understanding coal mining areas and their soils in Czechia are discussed.

Coal mining in the Czech Republic

Coal has traditionally been a significant part of the Czech Republic's energy mix. The Czech Republic has experienced a shift in the raw materials utilized for energy production over time; however, coal has remained a significant source since the eighteenth century (Sivek et al., 2020). The changes in total energy supply by source in the Czech Republic between 1990 and 2021 are presented in Fig. 1.

In the Czech Republic, the only fossil fuels that can be produced domestically are brown and hard coals. Nuclear fuel and all other fossil main sources are imported. The Czech brown coal extraction is performed in open-pit mines, and its calorific value ranges from 10 to 19 MJ/kg. Because of its lower value of calorific, brown coal has been traded in neighboring areas. The Czech Republic ranked first among all candidate nations in brown coal exploitation in 2001, and second among the EU-15, after Germany (Rečka & Ščasný, 2016). Even to this day, there has been no change in this situation (EC, 2015). However, in the coming years, several Czech brown coal mines are expected to be shut down, leading to a reduction in the overall volume of brown coal extraction. The decision made by the government regarding the territorial limits of brown coal mining will determine this reduction rate. As per the 2013 estimations, the available reserves of brown coal are roughly 840.5 million tonnes, with an additional 269.3 million tonnes of deposits established apart from the territorial mining limits (Rečka & Ščasný, 2016).

Coal mining in the Ostrava region, in the northeast of the Czech Republic, dates back to the second half of the eighteenth century. The rapid growth of coal mining, alongside iron works, commenced during the 1840s (Mulková et al., 2016). The 1970s and 1980s were the golden years of coal production. Following this time, coal mining fell down quickly, and nowadays the majority of coal mines are closed

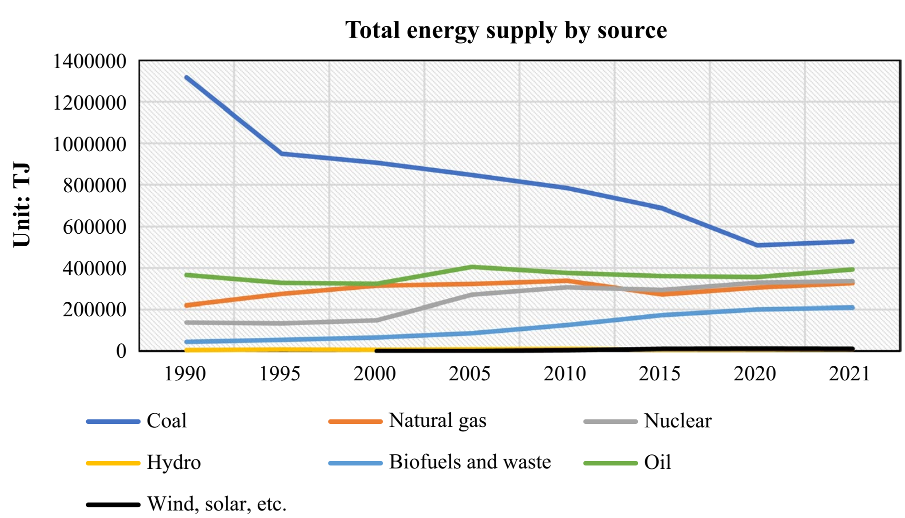

Fig. 1 Total energy supply by source in the Czech Republic between 1990 and 2021 (www.iea.org/countries/czech-republic)

(Mulková et al., 2016). The Sokolov brown coal basin, located in North Bohemia, Czech Republic, is considered one of the most extensive coal basins in Central Europe. As of 2017, this basin's total annual production of brown coal amounted to approximately 6.9 million tons. Coal mining operations were launched in the 1750s in this region, initially in the form of underground mines. Subsequently, from the 1950s onward, mining activities have persisted in the form of open-pit mines. At present, mining operations have been restricted and attempts are started to restore the areas affected by mining spoil and abandoned mines throughout the region. In addition, there are four significant coal power plants operating in the North Bohemian region (Zádrapová et al., 2019).

Origins of the coal industry

The Czech Republic has a notable historical legacy in coal mining that can be traced back to the medieval period. When the country's railway network was built in the middle of the nineteenth century, it connected the country's major industrial areas with the sites of coal reserves, which led to the industrial expansion of coal mining (Frantál, 2017). However, coal's golden period came after World War II when it supplied most of the fast-expanding demand from West Germany's post-war recovery and communist countries' heavy industry development (Sram, 2012). Coal was recognized as the "life blood" of the metallurgical, heavy, and energy industries throughout the communist era (1948–1989), which was supported and developed as one of the main sectors of the national economy (Říha et al., 2005). The mining industry and consumer demand both experienced dramatic increases throughout the 1960s and 1970s, peaking in the 1980s. This is relevant to lignite as well as to hard coal. The extraction of hard coal was primarily centered in the Upper Silesian and Kladno areas, leading to the subsequent development of heavy industry and metallurgy in these regions. Regions rich in lignite, such as Northern and Western Bohemia, were transformed into power production sites (Korski et al., 2016). Several areas especially in Northern Bohemia, including the areas of Most and Sokolov, experienced environmental destruction as a result of this planning tendency (Frantál, 2017).

Coal mine sites

Coal reserves in the Czech Republic include lignite coal and bituminous coal (black coal). Currently, the mining of only brown and bituminous coal persists, while the mining of lignite has been discontinued (Lehotský et al., 2019). Hard coal reserves in the Czech Republic are 23 million tons, with the greatest quantities found in the Upper Silesian coal basin. This coal basin is one of the largest in Europe, covering 6500 square kilometers. The majority of this basin takes place in Poland, while approximately one-sixth (1200 km^2) is in the Czech Republic, where it is known as the Ostrava-Karviná Basin. The Czech Republic has brown coal reserves amounting to 682 million tons that are economically recoverable. The North Bohemian brown coal basin is the major deposit of brown coal and the most extensive mining region, spanning 1400 square kilometers. It is situated at the foothills of the Krušné hory mountains, adjacent to the German state of Saxony, and in nearby to the towns of Ústí nad Labem, Teplice, Most, Chomutov, and Kadaň (Fig. 2). The thickness of the coal seams in this region ranges between 15 and 30 m at depths of up to 400 m. Apart from a coal basin located in North Bohemia and another basin situated nearby Sokolov town, there exist coalfields in the southern region of the country. However, these coalfields are considered non-economically viable (EURACOAL, 2018). The Czech Geological Survey estimates that there are 714 million tons of brown coal and 25 million tons of bituminous coal in total exploitable reserves (IEALehotský et al., 2019; Starý et al., 2017). Table 1 presents fundamental statistical data regarding the country and its coal sectors, and Table 2 presents an overview of the structure of the domestic coal industries.

Bituminous coal is controlled by one company, Ostravsko-karvinské doly (OKD), and is mined underground. Reserves are limited, and there are currently no goals to develop any additional sites. Numerous structural issues, including lower prices for coal on the global market, have contributed to the decline of the bituminous coal mining industry (Rečka & Ščasný, 2016). This resulted in the bankruptcy of OKD (IEA,). The Czech government intervened to prevent widespread job losses, bought the company with all of its debts, and intends to terminate mining operations by 2026. In Northern Bohemia, opencast

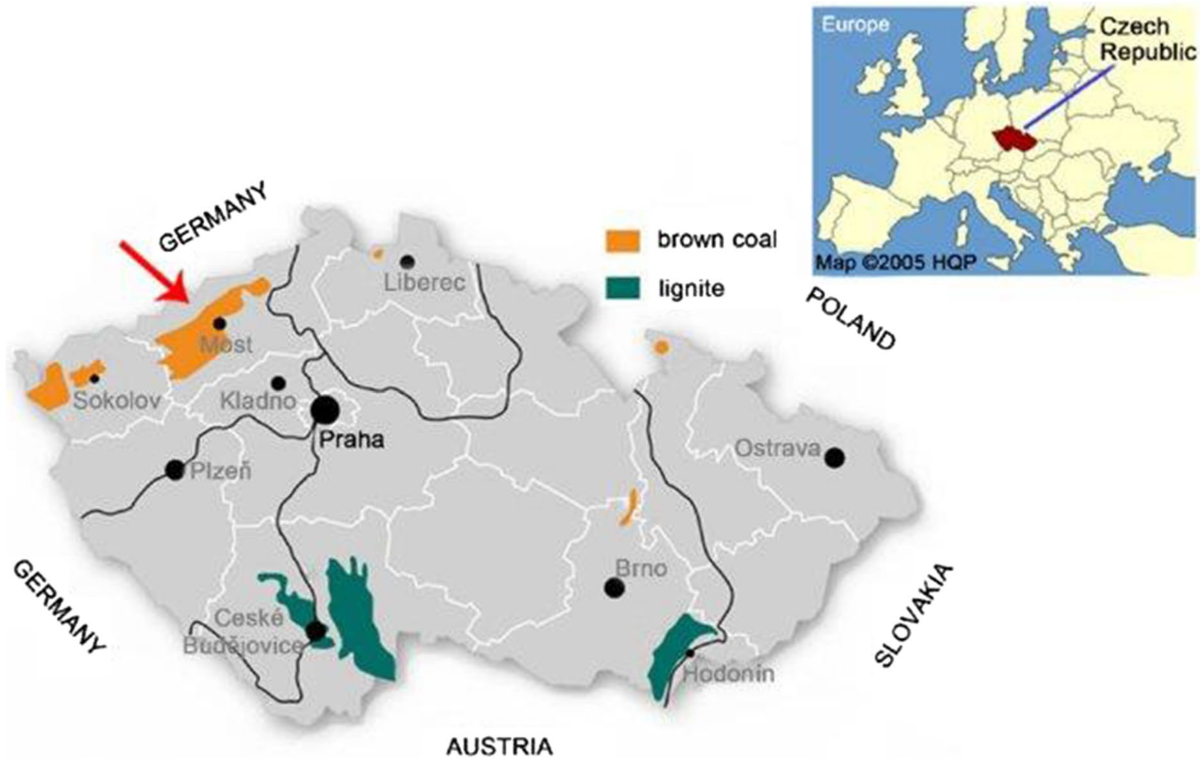

Fig. 2 Location of coal reserves in the Czech Republic (*Source* Vráblík et al., 2017)

Table 1 Statistical summary of the coal regions

	Czech Republic	EU28
Population (million)	10.5	510.3
Real GDP (1000 euros) per capita	16.5	27.1
Emissions of greenhouse gases (tonnes of CO_2 equivalent) per capita	12.4	8.7 (temporary)
Solid fuels: initial output (1000 tonnes)	45.3	481.3
Non-renewable solid fuels' percentage in the final consumption of energy	39.7%	14.6%
Solid fossil fuels' percentage in gross electricity generation	50.4%	21.2%
Number of employees in coal mining	17,299	150,229

Source Modified: Osička et al. (2020), EC (2019)

mines are run by four brown coal mining companies, where one is operating in the Sokolov Basin, while the North Bohemian basin possesses three of them. In contrast to bituminous coal, brown coal's future in the Czech Republic is less certain. Its contribution to generating power is expected to become less important over time. However, the heating industry will continue to rely heavily on domestically mined coal for the foreseeable future (Lehotský et al., 2019).

The Czech coal industry has traditionally played an important role in the national economy and will continue to engage in. In 2018, coal accounted for 49.5% of total gross power generation. By 2040, coal's contribution to gross electricity generation should fall between 11 and 21%, based on the State Energy Policy, which was adopted in May 2015. The Czech Republic is expected to experience an increase in the utilization of fossil gas, biogas, and potentially

Table 2 Coal industry in the Czech Republic

Mining company	District	Coal type	Type of mining	Active mines	Output (Mt/year)	Ownership
OKD	Upper Silesian Basin	Bituminous	Underground	5	8.3	Private
Severočeské Doly	Northern Bohemian Basin	Brown	Opencast	2	21.7	ČEZ
Seven	Northern Bohemian Basin	Brown	Opencast	1	3.8	Private
Vršanská Uhelná	Northern Bohemian Basin	Brown	Opencast	1	6.5	Private
Sokolovská uhelná	Sokolov Basin	Brown	Opencast	2	6.4	Private

Source Modified: Osička et al. (2020), IEA (2016a, 2016b)

synthetic methane and hydrogen, as coal-fired power generation is gradually phased out. Moreover, the Czech Republic is implementing an extensive plan to improve and renew coal-fired power plants in North Bohemia as to guarantee the sustainable application of coal in the future (EURACOAL, 2018).

Territorial ecological restrictions on coal mining

The Czech Republic ranks in the top three of EU members for consuming coal alongside Germany and Poland. In conjunction, they constitute up to 57% of the overall coal consumption in the EU (Lehotský et al., 2019). Coal availability is directly correlated with this type of consumption because most utilization occurs near domestic mining sites. Exports and imports of brown coal are extremely few because there is no market for it internationally (Starý et al., 2017). The excessive mining and consumption of coal that occurred during the time of communism created the foundation for the development of the coal mining industry. The aforementioned condition has caused serious environmental problems in Northern Bohemia and the Upper Silesian Basin, including severe temperature inversions, water contamination, soil erosion, and acid rain (Říha et al., 2011). People living in these areas endured higher health problems resulting from pollution (Sram, 2012). These impacts were mainly attributed to the reason that most of the coal produced in mining areas is utilized in power plants near mining sites (Lehotský et al., 2019). Furthermore, open-pit mining has caused a far more profound effect on the environment of Northern Bohemia than the underground mining of bituminous coal in Upper Silesia. This practice, which began in the 1950s, resulted in the forcible relocation of residents, the destruction of many villages, and long-lasting alterations to the landscape (Říha et al., 2011).

In 1991, the Czech Republic's government decided to set "Territorial Environmental Limits" for brown coal mining in the North Bohemia coal basin (Fig. 3). According to a recommendation by the Minister of the Environment, the limits were established by Czech Government Resolution No. 444 (1991). The environmental concerns that led to the implementation of these limitations were intended to reduce the ecological damage caused by the surface mining of lignite and the generation of electricity in the North Bohemian lignite basins. They were also planned to decrease the effect on the land surface, cities, and other facilities. These restrictions further functioned as an assurance from the government to the areas that the local environment would not degrade further and that locals would have stable environments in which to invest, renovate their homes, and so on (Vlček & Černoch, 2012; Vlček & Jirušek, 2015). Almost three decades later, the country continues to be largely dependent on coal, providing 42% of the heat generated in central heating systems and 39% of the gross electricity generation (Černoch et al., 2019). The restrictions currently prevent about 900 million metric tons of coal from extracting from five mining locations in the Northern Bohemian and Sokolov Basins (IEA, 2016a, 2016b). The potential for a major expansion of mining operations takes place at only two sites in the Northern Bohemian Basin: the Blina mine and the Czechoslovak Army mine (ČSA) (Černoch et al., 2019).

In the North Bohemian Lignite District, the operational period of the ČSA opencast mine (in what is known as 2nd phase) has been reduced from 2060 to 2022 due to the aforementioned restrictions, and the lifespan of the large Blina opencast mine also has

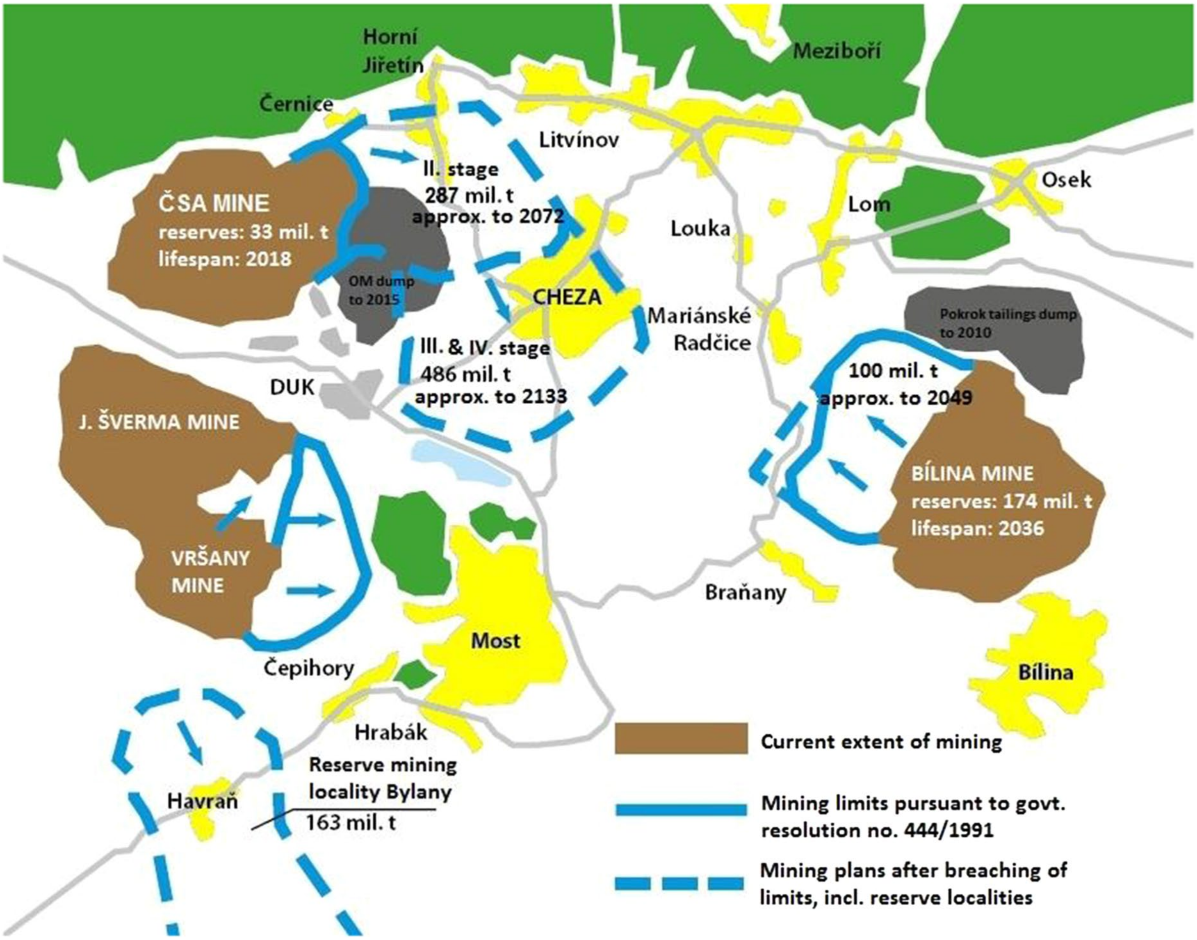

Fig. 3 The North Bohemian brown coal mining limits and plans after breaching the limits (yellow = built-up areas, green = forested areas). Adopted from Kořeny (2012)

been reduced from 2050 to 2035 owing to the same factors. Accordingly, the long-term development prospects of the Czech energy sector, which relies heavily on the exploitation of native coal reserves, have been severely restricted by the limits that have been established (Frantál, 2016; Voros et al., 2018; Lehotský et al., 2019). The political objective of the Czech Republic is to fulfill its commitments to international agreements like the Convention on Long-Range Air Pollution (Dvořák et al., 2017).

Coal mining impacts on soil

All elements of ecosystems are affected by coal mining, particularly opencast mining (Bradshaw, 1997). During the process of opencast mining, the material known as "overburden" that is located on top of the mined minerals is extracted and placed in a heap. Two potential locations exist for this heap: inside the mine pit (known as an internal heap) and outside of the mine (known as an external heap). Consequently, whatever ecosystem existed before mining activity or external heap deposition is fundamentally eliminated by excavation or burial (Bell & Donnelly, 2006). Mineral processing, which produces tailings and other deposits, can impact or degrade additional areas (Frouz, 2021). A simplified schematic of the coal mining process is shown in Fig. 4.

Earlier studies indicated that the chemical and physical characteristics of soil could be utilized to determine soil health. Soil physicochemical features,

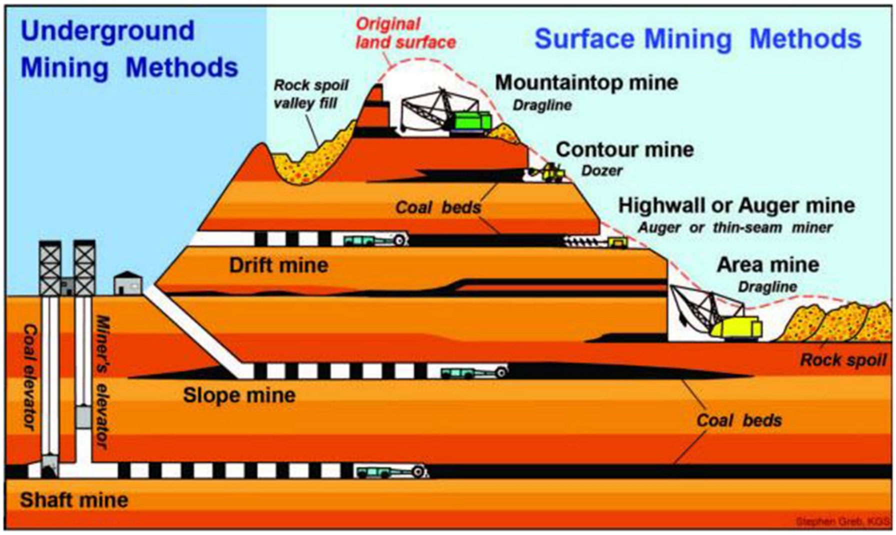

Fig. 4 Coal mining process (*Source* Stephen Greb, 2009)

such as horizons, structure, microorganisms, and nutrient cycles, will be impacted by coal mining in and around the mining region (Huang et al., 2018; Šourková et al., 2005; Wang et al., 2018). In coal mining regions, topsoil gets mixed with overburden materials, and weakly bonded overburden soil transported by wind may also have an impact on the soil's physicochemical characteristics (Rai et al., 2010). During the process of coal mining, the employing of heavy vehicles for transporting of coal and overburden material results in considerable ground pressure. Consequently, the soil in coal mining regions becomes compacted, which leads to increased bulk density, decreased porosity, and a reduced capacity for holding water (Maiti, 2013; Pandey et al., 2014). Horizons do not exist in these soils, and they typically do not have soil structure either. Concerning other soil features, overburden soils are significantly distinct from the native soils in the natural environments around them. They usually have extreme soil texture and high pH levels (too alkaline or too acidic) (Frouz, 2021). The capacity of soil to retain water and hold nutrients is specifically associated with soil particles and total N contents (Bera et al., 2020).

Impacts on soil physical properties

At least two horizons exist in mine soils: a lower horizon with weak structure and different rock fragment sizes and a recognizable surface horizon with some organic matter and a significant amount of fine earth material (Johnson & Skousen, 1995). According to the findings of an investigation on mine soil, the thickness of the surface horizons ranged from 2.5 to 10 cm after 1 to 40 years of reclamation of mine soil (Haering et al., 1993). In mine soils, it has previously been discovered that the thickness of the solum (both the A and B horizons) increases with increasing age (Thomas et al., 2000). A subsurface horizon has been documented to have formed in mine soils of different ages, spanning a few years to decades, as a result of the complex features of mine soils (Ciolkosz et al., 1985; Schafer et al., 1980). Although young mine soils typically possessed massive structures, old mine soils had cambic-like horizons, which were identified in 50-year-old mine soils with shallow depths that barely met cambic criteria (Roberts et al., 1988).

The texture of the mine soils is different from site to site. Some are identical to the undisturbed soils around them, while others are noticeably different due to the replacement of native soil materials with different textured overburden (Sencindiver & Ammons, 2000). In most of the world, soil textural classification is founded on examinations of particle size (Nemes & Rawls, 2004). The weatherability of rock and spoil materials, the length of time since reclamation, and weathering conditions are only a few of the variables that impact the particle size distribution of mine soil (Haering et al., 1993; Wood & Pettry, 1989). Under the same conditions, the average soil particle size of mined areas turned into finer than that of unmined areas (Wali, 1999). Poor water retention and disturbed soil structure are common in mining soils due to their coarse texture with high sand concentration and comparatively low fine (silt, clay) particle contents (Sena et al., 2021). Particularly, soils rich in clay and silt have a favorable tendency for the formation of the argillo-humic complex, leading to increased total N (Dempster et al., 2012). At the same time, the combined impacts of aboveground (climate, vegetation, and grazing) and belowground (soil characteristics) elements led to changes in total N and total C (Lozano-García et al., 2017).

Bulk density is the most commonly employed measure for determining mine soil compaction in a mining area (Panayiotopoulos et al., 1994). Reclaimed mine soil often has greater bulk densities (1.55–1.86 mg m^{-3}) because of the heavy machinery employed in the reclamation and mining processes (Shrestha & Lal, 2008). The capacity of compacted soils to exchange air and water is directly impacted by compaction. Therefore, additional characteristics like soil porosity, strength, and moisture are also required to accurately determine mine soil compaction (Lipiec & Hatano, 2003). Low soil porosity is correlated with high bulk density. Soil aeration is most frequently determined via air-filled porosity, and a value of $<10\%$ is considered optimal for plant growth (Lipiec & Hatano, 2003).

Spoil material which is excavated from great depths may be hydrophobic. Given this characteristic, the reclamation of the soil is a precondition for the rehabilitation of the ecosystem at post-mining sites. This restoration must take into account both the hydrological properties of the soil as well as the water regime (Brady & Weil, 2002; Frouz et al., 2006). From post-mining sites, high water repellency has often been reported (Sonneveld et al., 2003). Even so, dry soil with an elevated level of organic matter appears to have some water repellency (Sonneveld et al., 2003). Water repellency has been shown to limit the moisture content of some soils, according to Wang et al. (1998) and Doerr et al. (2006). The quantity of available soil water is determined by the interaction between precipitation and the infiltration rate of reclaimed mine soil as well as conditions of groundwater (Evans et al., 2015). Water infiltration is influenced by various factors such as coarse fragments, soil aggregation, and soil texture. In addition, the soil biota activity and soil organic matter regulated soil aggregation (Bronick & Lal, 2005). Vegetation deficit and soil compaction are two factors that contribute to organic matter deficiency in reclaimed mine soil, perpetuating the cycle of poor quality (Feng et al., 2019). Soil infiltration in reclaimed mines has been shown to be affected by large bulk densities, and infiltration rates have been proven to alter over time. Immediately after mining and reclamation activities, surface soil compaction can reduce infiltration rates (Weiss & Razem, 1984). Consequently, in newly formed mine sites, soil surface hydrology is often not in equilibrium. The study conducted in central Pennsylvania revealed that during the initial phase of reclamation, low infiltration rates were identified. However, over a period of 12 years, the infiltration capacities were found to have increased (Ritter & Gardner, 1993).

Vegetation cover was also found to have a significant impact on soil infiltration in recovered mines (Zipper et al., 2011). According to reports, reclaimed post-mining areas consume more water than unreclaimed sites since the former has far more plant biomass (Frouz et al., 2008). It found that the rate of infiltration in reclaimed mine soil was ten times fewer than that in the control forest because the conversion of natural forest to different land uses caused by mining greatly decreased the content of nutrients and soil quality (Ahirwal & Maiti, 2016). In addition, it has been demonstrated that degraded mine soils have a lower water-holding capacity than soils that have been properly amended (Camberato et al., 2006). In a study on a post-mining spoil heap near Sokolov, Cejpek et al. (2013) showed that although the reclaimed post-mining sites had a higher water-holding capacity than the unreclaimed ones, the two types of sites did not differ significantly in their water limitation. Also, on the same site, Kuráž et al. (2012) showed that the field water content of the soils decreased as the time of dump overgrowth increased. In addition, along with the age of succession, a reduction in soil temperature has been observed in the layer inhabited by the roots (in the diurnal variation).

Impact on chemical properties of soil

Overburden materials most frequently serve as the parent substrate for the formation of soil (Karu et al., 2009). Organic carbon levels in the soil are a reliable indicator of both soil health and the effectiveness of reclamation activities (Bodlák et al., 2012;

Courtney et al., 2013). It alters the structure of the soil as well as its sorption capacity, and it has an impact on infiltration rates, porosity, and water storage (Brady & Weil, 1999). Accumulation of organic matter in the soil can result in carbon sequestration, which can reduce the rise in the atmospheric concentration of CO_2 (Lal, 2004). In mine soils, in addition to the soil organic matter that was lately formed from plant leftovers, it is frequently possible to find forms of fossil organic carbon, including kerogen or coal (Ussiri et al., 2014). In coal mining regions, one of the common fossil forms of organic carbon is coal rich in aromatic compounds (Vindušková & Frouz, 2013). However, considerable levels of other organic materials such as kerogen may be contained in the overburden, which is comprises aliphatic, aromatic, and asphaltene compounds (Kříbek et al., 1998). The sequestration of soil organic carbon can overestimate due to the presence of fossil organic carbon. The soil formation assessment in post-mining areas, comparing natural pristine soils and mine soils or comparing carbon sequestration between mine soils, is significantly hampered by the lack of a commonly acknowledged method for determining fossil and recent carbon (Vindušková and Frouz, 2013; Mukhopadhyay et al., 2013). In this regard, many studies have been conducted worldwide. For example, soil degradation from coal mining in Mongolia was documented by Kou et al. (2022), who found significant sand contents and comparatively low fine particle contents. Their findings imply that coal mining has accelerated soil desertification in the two coal mines, decreasing N content and elevating the C/N ratio. In the Indian coalfields of Jharia and Raniganj, Pandey et al. (2014) reported that broad coal mining in the region has decreased the soil's pH, N content, and available form of phosphorus. Moreover, there are some other investigations in the Czech Republic as follows:

In unreclaimed post-coal mining areas nearby Sokolov, Woś et al. (2023) indicated that despite variations in soil C storage with site age, the mean value of the age gradient was 0.50 t C/ha year-1, showing that unreclaimed areas with ecosystems that formed through natural succession were able to accumulate organic matter in soil and become a sink for C. In this study, as opposed to C, the content of soil N, total P content, and N stock did not alter considerably over time. On the same site, the development of the soil in two post-mining chronosequences from open-pit coal mines was assessed by Abakumov et al. (2013). The findings showed significant differences in the initial development of soil between reclaimed areas planted with particular tree species and unclaimed sites with naturally occurring vegetation. Additionally, in the reclaimed sites, C and N accumulated in a shorter period. Furthermore, despite an increase in aromaticity with age, the humic acid levels in the spontaneous sites were lower than in the reclaimed sites. In another study, in a brown coal mine deposit area nearby Sokolov, Urbanová et al. (2011) reported that while the C/N ratio and the pH declined during succession, the level of organic carbon and total N in the soil increased. In a different area, Ivanov et al. (2009) evaluated the mine soils at a coal waste pile from the Kukla-Václav Nosek mine (Southeastern part of Czechia). According to their findings, the primary pedogenetic process during the early phases of mine soil development at the waste pile was extensive humification. Also, granular aggregate stability was highest in the youngest soil, which was found at the top of the waste heap. Moreover, the biological recultivation had a significant impact on the top soils of the Kukla waste heap in terms of humus quality. Table 3 shows some physicochemical properties of soil in coal mining areas.

Potentially toxic elements and organic pollutants

Although coal has remained among the most significant fossil fuels regarding energy generation, it also has the potential to be a significant source of environmental contamination since it contains a variety of contaminants (Gopinathan et al., 2022c; Zhang et al., 2020). According to Kabata-Pendias and Pendias (2001), the primary contributors to atmospheric pollution with potentially toxic elements (PTEs) are the combustion of coal and other fossil fuels as well as the smelting of non-ferrous and iron metals. Increased levels of PTEs (Cr, Cd, Pb, As, Zn, Cu, etc.) in the environment are commonly associated with the extraction and subsequent processing of metal ores and/or coal. Although mining only impacts limited regions, the environmental impacts it causes are significant, as noted by Wahsha et al. (2016). Furthermore, the mine tailings can have an impact on the nearby farmland since the tailings and waste rocks can transfer across the lands and combine with the soil. Consequently, the toxicity of PTEs

Table 3 The physicochemical properties of unreclaimed soils affected by coal mining

Country	Site	pH	OM	TN (%)	TP (%)	TC (%)	Clay	Silt	Sand	C/N	CEC	References
China	Linhuan coal mining area	6.63	26.96	4.07	0.07	na	na	na	na	na	na	Tang et al. (2023)
India	Raniganj basin	5.86	na	na	na	1.80	0.4	53.2	46.4	na	na	Chakraborty et al. (2023)
Mongolia	Shengli Mine	8.4	na	0.08	na	1.9	2.9	13	84	na	na	Kou et al. (2022)
China	Zhangji Coal Mine	6.63	25.68	3.70	75.63	na	7.35	32.06	60.59	na	28.26	Li et al. (2019)
CZ	Sokolov	7.09	na	0.38	na	7.18	17.9	na	na	23.2	na	Abakumov et al. (2013)
CZ	Sokolov	6.9	na	na	na	na	18.6	54.7	26.7	ng	na	Kuráž et al. (2012)
CZ	Sokolov	6.2	na	0.52	na	na	na	na	na	59.9	na	Urbanová et al. (2011)
CZ	Sokolov	6.2	29.6	0.55	4.8	na	na	na	na	na	na	Baldrian et al. (2008)
CZ	Bohemian brown coal basin	7.05	na	0.17	na	1.72	32.67	37.33	30.00	10.08	na	Růžek et al. (2001)

na not analyzed

can lead to a decline in land productivity. Additionally, elevated element contents can be transferred into the food chains through the crops that are produced (Gonzalez-Fernandez et al., 2011). In order to effectively reduce contamination, it is crucial to accurately assess the level of PTEs in the soil (Rouhani et al., 2023b). Although PTEs are vital for vegetation, they can have several types of negative impacts when the threshold level is exceeded (Feng et al., 2022; Nagajyoti et al., 2010).

One of the most significant and commonly debated coal-borne contaminants is polycyclic aromatic hydrocarbons (PAHs). They are varied organic compounds without substituents that contain two or more condensed aromatic rings, such as benzochrysene, dibenzanthracene, benzo[e]pyrene, benzo[a]pyrene, benzo[k]fluoranthene, benzo[g,h,i]perylene, chrysene, benzo[b]fluoranthene (Ghosh et al., 2022; Lawal, 2017). Apart from their pyrogenic origin, PAHs may also have diagenetic/catagenetic origin in coal (Ghosh et al., 2022). Depending on their chemical composition and the number of aromatic rings, these compounds have different physical and chemical characteristics. In general, PAHs possessing > four aromatic rings, also known as high molecular weight PAHs (e.g., benzol(a)pyrene, naphthalene, coronenes, etc.), exhibit higher stability, toxicity to organisms, reduced biodegradability, and increased adverse effects on the environment (Igwe & Ukaogo, 2015; Lawal, 2017). PAHs are regarded as the by-products of incomplete ignition of any organic substance, consisting of fossil fuels (Holoubek et al. 2001). Therefore, the major PAH sources that pose a high risk of environmental pollution are industrial technologies, traffic, and urban regions (Igwe & Ukaogo, 2015). Some PAHs are widely recognized for their carcinogenic, mutagenic, and teratogenic properties, thereby posing a significant risk to human health and well-being. Inhalation exposure to PAHs is primarily associated with an increased risk of developing lung cancer (Kim et al., 2013). PAH mixtures' inflammatory and irritant effects on the skin have also been documented. Naphthalene, benzo(a)pyrene, and anthracene are known to directly irritate the skin. Additionally, benzo(a)pyrene and anthracene have been found to induce skin sensitization, resulting in allergic reactions in both humans and animals (Abdel-Shafy & Mansour, 2016). Health impacts from chronic or long-term exposure to PAHs can include lung function abnormalities, asthma-like symptoms, breathing problems, cataracts, kidney and liver damage, and reduced immune function (Diggs et al., 2011).

It is surprising that unburnt coal has seldom been regarded as a source of PAHs in sediments and soils (Ahrens & Morrisey, 2005). The original hard coals from the seam may have PAH concentrations of hundreds to thousands of mg/kg, along with the PAH that has been sorbed after being exposed to the environment (Stout & Emsbo-Mattingly, 2008). Walker et al. (2005) expressed this neglect by describing coal as a source of PAH that was previously unknown or unsuspected. Lower concentrations of PAHs were found in low rank coals, such as lignite, sub-bituminous coal, or brown coal. For example, a study by Püttmann (1988) detected PAH concentrations as low as 13 mg/kg PAH. The presence of these compounds in brown coals can be attributed to the breakdown of pentacyclic angiosperm-derived triterpenoids (Tuo & Philp, 2005). In Victorian brown coals from Australia Kashimura et al. (2004) detected semi-quantitatively naphthalene, coronene, dibenzo[a,h]pyrene, dibenzo[a,i]pyrene, benzo[b]chrysene, benzo[e]pyrene, benzo[a]pyrene, perylene, benzo[a]anthracene, chrysene, pyrene, anthracene, and phenanthrene. Li et al. (2023) identified alkylated PAHs in lignites from China. Picene, chrysene, and their alkylated derivatives are the most common PAH found in sub-bituminous coals. During the process of coalification, the patterns of PAHs undergo changes. This is due to the generation of primary products that possess higher thermodynamic stability, which occurs at the expense of less stable compounds (Achten & Hofmann, 2009). Low molecular weight aromatic compounds are formed at the boundary among sub-bituminous/high volatile bituminous coal. High volatile bituminous coal is the primary source of bi- and tricyclic PAH, which offer a pattern of compounds demonstrating structural similarity to natural precursor molecules such as phenanthrene derivatives, which are assumed to be generated from plant resins and steroids (Püttmann and Schaefer, 1990). As the coal rank increases, there is a noticeable change in the pattern of PAHs. Initially, at lower ranks, there are higher levels of naphthalene and its alkylated derivatives. However, as the rank of the coal increases, there is a relative increase in the presence of 4–6 ring PAHs (Ahrens & Morrisey, 2005). The oxygen content is reduced simultaneously, leading to decreased concentrations of hydroxylated aromatic compounds, specifically phenols, which are commonly found in lignite (Achten & Hofmann, 2009).

The primary PAHs sources in Chinese soil were found to be coal combustion and vehicle exhaust emissions, according to Zeng et al. (2019). However, Gao et al. (2019) examined into the PAHs distribution in raw coal and found that it contains considerable concentrations of low molecular weight PAHs. In this study, bituminous coal was found to have greater PAH levels than lignite, and they measured a total PAH content in coals of 10,540 ± 7973 mg/kg. Strong correlations between the PAH levels of coal, soils, fly ash, and particulate matter ($PM_{1\text{-}2.5}$ and $PM_{2.5–10}$) in a coal mining region have been identified by Zhang et al. (2020), demonstrating that PAHs deposition and emission are the major contributors to these pollutants in soil. In addition, similar to heavy metals, PAHs have the tendency to be strongly adsorbed by the coal-derived particles and fine coal found in sediments and soils (Yang et al., 2008). Ashes or tailings can be found in the soils around coal mining sites, and the presence of ashes suggests that the PAHs may have originated from pyrogens, while the tailings containing PAHs are primarily of petrogenic origin (Hindersmann & Achten, 2018).

Many scholars have reported that as distance increases from coal mines, the levels of PTEs and PAHs in the plants and soil decline (Shi et al., 2013; Song et al., 2023; Yakovleva et al., 2016). Additionally, it has been also reported that the soil's surface layer has higher element contents than the deeper soil layers (Kumar et al., 2023; Liu et al., 2017; Ma et al., 2008; Ouyang et al., 2018). Furthermore, many researchers have reported the direct negative effects of the coal mining industry on urban environments, where frequently extremely high levels of different risk elements have been identified in urban soils and particulate matter (Jia et al., 2023; Li et al., 2018; Lin et al., 2019; Zhang et al., 2023). The contaminated soils around coal mining area by PTEs were the focus of many researchers around the world, most notably in Asian countries (Table 4). For example, in a coal mining area in northwest China, Abliz et al. (2018) showed that the mean concentrations of Zn, Cu, and Pb were lower than the Chinese soil environmental quality criteria and the local background values, whereas the mean concentrations of As, Hg, and Cr

Table 4 Total PTE and PAHs concentrations (mg/kg) in coal mine areas in the Czech Republic and other countries

Location	Country	ΣPAHs	HMs (mg/kg)								References
			Cd	Hg	Cu	Ni	Pb	Zn	As	Cr	
Litvínov city area	CZ	na	0.468	na	31.1	26.0	48.9	175	41.7	45.6	Hanousková et al. (2021)
Sokolov coal basin	CZ	na	0.987	na	36.1	19.1	40.7	118	33.7	40.0	Zádrapová et al. (2019)
Ostrava	CZ	na	0.21	0.19	21.11	na	37.71	204.569	na	17.46	Doležalová Weissmanová et al. (2019)
North Bohemian region	CZ	8,02	0.33	0.17	35.67	32.66	51.55	107.96	33.77	na	Vácha et al. (2015a)
Reclaimed soils of the Sokolov region	CZ	na	0.08	na	1.67	1.25	16.70	29.06	1.98	1.35	Milan et al. (2006)
Tianshan Mountain	China	na	na	na	19.28	na	16.69	47.84	33.48	68.51	Abliz et al. (2018)
Jharia coal field	India	na	0.4	na	66.3	64.1	27.8	127	na	43	Pandey et al. (2015)
Proposed limit values for CZ		–	0.5	0.3	60	50	60	120	20	90	Vácha et al. (2015b)

na not analyzed

were higher than these levels. In another study around a coal mining area in India, Pandey et al. (2015) reported high enrichment of PTEs near coal mining areas. In this study coal mining activities and mine fires have been found to be the primary sources of Cr, Cu, and Ni in the soil.

In the North Bohemian region, Boahen et al. (2023) determined the environmental risk of As, Be, Cd, and Zn in impacted soils by brown coal mining. In this study, the maximum levels of studied elements in the soils were found to be higher than the preventive values, with the individual pollution index value reaching as high as 58 for As in the mountain regions, suggesting extremely high levels of pollution. Additionally, a slight degree of pollution was documented with regard to the Cd. In another study around the most brown coal basin, Skála et al. (2021) demonstrated that the soil samples from the mountainous area (mineralization from geogenic processes) and those from the basin area (intensive coal mining) can be distinguished clearly by the geochemical pattern of the analyzed elements. Furthermore, the increased risks of As in this study are associated with human-driven alterations in the coalfield area, where coal fly ash leads to higher respiratory as well as gastro-intestinal bioaccessibility. Pb also shows an opposing pattern, with greater concentrations on coarse particles, implying a livestock risk in non-forest mountainous locations. In the Litvinov city region (North Bohemia), which is impacted by coal mining and processing, as well as extensive industrial activity, Hanousková et al. (2021) indicate increased levels of Zn, Pb, Ni, Cu, Cd, and As in soils. Risk assessment values in this study suggest that Cd and Zn are highly bioavailable. Moreover, the PAH levels in soils are high due to dense traffic, industrial activity, and heavy coal mining activities. In addition, Kotalová et al. (2011) reported high levels of PAH in the soil and plants in an urban area of Ostrava city that is impacted by coal mining and heavy industrial activity.

Sedlacek et al. (2020) showed a clear vertical distribution of all contaminants in the sedimentary record at the Czech-Polish border in Oxbow Lake sediments affected by coal mining. In this area, because of political and socio-economical changes in former Czechoslovakia (now the Czech Republic), the highest concentrations occurred throughout the 1970s and 1980s, while a declining trend started after 1989. According to the findings of Zádrapová et al. (2019), the soils from the Sokolov area, which have been impacted by coal mining and combustion, exhibit the greatest Cd bio-accessibility. They also noticed significant As and Be bio-accessible pools. In the North Bohemian Coal District, Vörös et al. (2018) found that sediments in the middle part of the River Bílina are extremely polluted. They reported that the weathering of old coal waste dumps and combustion residues contributed to increased levels of Hg in sediments. In another study on this river, Vörös et al. (2019) showed higher concentrations of As, V, Ni, Cr, and Pb in all of the stream sediment samples. In a study on agricultural soils impacted by heavy industry and coal mining from Northern Czech Republic, Vácha et al. (2015a) revealed that the North Bohemian area has elevated levels of As and Be, while the North Moravian area has elevated levels of Cd and PAH. They concluded that heavy industries and hard coal mining in North Moravia, as well as, lignite mining in North Bohemia have all contributed to the pollution of the soil ecosystems. An earlier study on forest floor humus in the entire territory of the Czech Republic by Suchara and Sucharová, (2002), showed no major differences in concentration classes of elements in forest humus.

Coal surface mining has been the primary human activity in North Bohemia for about two centuries. Its impacts can be seen not only in the environment as a whole but also in the landscape, most notably through its detrimental impacts on human health. This includes not just those inhabiting very close proximity to the surface quarry but also those in more remote areas, where potentially toxic substances are transported by the area's dispersive and climatic conditions. PM_{10} dust particles, SO_2, NO_x, and CO are the most common by-products of the coal mining and processing industries. Additionally, these pollutants have the biggest impacts on the respiratory and circulatory systems. The region of Ústí nad Labem, specifically the districts impacted by mining activities such as Ústí nad Labem, Teplice, Chomutov, and Most exhibited the most unfavorable health indicators in the Czech Republic. These indicators consist of median life expectancy, cancer mortality rate, occurrences of lung cancer, and cancer in general, along with the mortality rates for infants (Vráblík et al., 2017). North Bohemian emissions in the 1970s amounted to 1.2 million tons of SO_2 and nearly 1 million tons of solid contaminants. Natural circulation has become worse, especially during the summer, by the high level of air pollution, which decreased the quantity of sunlight that reached the ground surface, especially in basinal districts (Anděl, 1990). Acid rain, with a pH of 3.4 on average in 1985, was also associated with air pollution. As a result, the acidity of the rain had an impact on the acidity of the soil. The available information indicates that there was a 20% increase in soil acidity between the years 1970 and 1983. Furthermore, in 1970, approximately 49% of agricultural land was characterized as acidic, while in 1983, this proportion had risen to 56% of the total area (Rychlíková, 2015).

Biological properties

The mechanisms involved in nutrient, energy, and organic matter cycling are controlled by soil biota. In order to assess the conditions for recovery in mining areas, soil fauna is frequently utilized as an indicator of soil quality since its biodiversity reflects the ecosystem metabolism. Microhabitat conditions, which represent the organic matter distribution as a key factor impacting microclimate, are strongly correlated with the abundance of soil fauna (Frouz et al., 2011). During the surface coal mining process, when topsoil is removed, the amount of organic matter in the soil immediately decreases. As a consequence, the soil organism habitats will be significantly changed. Since the soil profiles have been fundamentally reversed, those substrate components may have fossil C which are susceptible to erosion, nutrient shortage, and inappropriate water regimes (Frouz et al., 2006; Scullion & Malinovszky, 2010). The reconstructed soils have disturbed the biological activity's equilibrium in the coal mine dump, and it will take a long time to carry out the processes necessary to restore a dynamic equilibrium condition.

The ecosystem of mined areas is impacted by the complex system of organisms that reside in the soil and are involved in several biological activities, including nitrogen and carbon cycling. These processes also have an impact on the chemical and physical characteristics of the soil (Frouz et al., 2006). The activity of many microorganisms, for instance, is impacted by parameters like aeration and pH, which alter the associated mechanisms engaged in nutrient cycling. The study of soil organisms' activity is a valuable tool for assessing mine soil quality resulting from significant coal mining disturbances. In recent years, microbial characteristics have been increasingly employed to evaluate soil restoration endeavors (Li et al., 2015).

Soil microorganisms serve as both a source and a sink of carbon and nitrogen in soil ecosystems, and the microbial biomass can estimate the net flux of these elements through microbial pools (Quadros et al., 2016). The deposition of acidic air contaminants and PTEs from coal mining activities can lead to changes in the microbial biomass on the soil surface (Asensio et al., 2014). Microbial biomass and activity are significantly influenced by the physicochemical features of the soil (Maiti, 2013). Enzymes have also a crucial role in catalyzing nutrient cycling and elemental turnover processes. These processes are responsible for the availability of essential elements including S, P, N, and C in the soil (Baldrian et al., 2008). In addition, they also contribute to the development of soil microbial communities, which are crucial for various soil processes and the provision of crucial soil ecosystem services (Gómez-Sagasti et al., 2012). Enzymes in the soil respond more quickly than any other soil feature, making them good indicators of alterations in soil quality and disturbances. The microbiological and biogeochemical equilibrium of the soil is disturbed by coal mining activities. Thus, soil enzyme activities in reclaimed sites serve as an indicator for assessing both soil fertility and soil health (Maiti, 2013).

Many scholars have utilized the microbial community as an ecological indicator in significantly degraded mining areas since it is susceptible to the soil environment and associated with various soil processes, such as nutrient cycling, organic residues decomposition, and degradation of toxic substances and contaminants (Kaschuk et al., 2010). For example, in an earlier study in a brown coal mine deposit region near Sokolov, Baldrian et al. (2008) showed a generally rising pattern of soil C, N, P, and K content, as well as soil microbial biomass, throughout the first stages of primary succession on spoil heaps. Following this primary phase, the nutrient content of the soil reduced, while the microbial biomass and enzyme activities remained stable or declined. Vicentini et al. (2020) also studied the soil and soil fauna development in two chronosequences of post-mining areas after opencast lignite mining nearby Most City. Both areas indicated a similar trend in soil chemistry throughout time, with a decreasing pH and sodium ion content. Additionally, leveled areas displayed random oscillations in the soil macrofauna, whereas wavelike areas exhibited a slow but steady increase.

Land reclamation

Large areas created by accumulating waste overburden components, which are in the beginning nearly devoid of life, are characteristic of brown-coal mining regions. The extraction of brown coal through open-cast mining procedure results in substantial landscape disruption, thus requiring the implementation of environmental and soil restoration measures. Typically, once the heaped material has settled (usually after 5–15 years), these areas are technically reclaimed and revegetated using either soil-improving mixtures, trees, or pasture. Conditions that are favorable for the survival of the vast majority of organisms can be provided as a result of this soil reconstruction, which focuses mostly on the top layers (Coleman et al., 2017; Frouz et al., 2008). Since it is a source of organic matter and provides the soil and soil organisms with nutrients essential to their health and sustainability, the top soil layer has an impact on the vegetation cover (Hendrychová et al., 2012). Soils from post-mining sites provide an opportunity to investigate the rate and timing of fundamental formation processes of soil (Frouz et al., 2008).

The Czech Republic has a long history of land reclamation, with the General Mining Law adopted by the Imperial Charter in 1854 implementing the first attempts to mandate the restoration of land changed by mining; nevertheless, until the end of World War II, restoration was performed out as a compensation measure (Vrbová & Štýs, 2008). The widespread destruction caused by opencast mining in the 1950s led to the introduction of additional laws, including the Mining Act in 1957. Based on this law, a firm mandate for restoring areas of land that had been degraded by mining was imposed. In the 1950s, the first steps were taken toward the systematic development of reclamation activities (Řehoř & Ondráček, 2009).

In the Czech Republic, mine reclamation is founded on the concept that post-mining sites have extremely adverse initial environmental conditions that prevent the initial growth of plants and other organisms (Schulz & Schwartzkopf, 2018). The mining companies operating in this country are obligated to reclaim the land to a more natural condition after their operations. To assess the costs and benefits of mining, the reclaimed landscape value should be raised by 80% compared to the baseline established before mining. This can be accomplished, for example, by increasing the ratio of habitats and vegetation types that have a high ecological classification value (Hendrychová, 2008). Mining areas in the Czech Republic have often been reclaimed using four methods, depending on the intended final use of the land: hydrologic, forest, agricultural, or other (mostly recreational). These are referred to as "planned" or "technical" reclamation and include numerous technical interventions and substantial initial management actions (Chuman, 2015; Prach et al., 2019). The process of technical reclamation typically entails three main activities. Firstly, a decrease in topographic heterogeneity via surface remodeling using heavy machinery, such as hydrotechnical engineering works, or in the case of stone quarries by filling the space with residual waste. Secondly, topsoil is added along with essential nutrients and, thirdly, accompanied by the sowing of a regular trefoil-grass mixture or tree planting (Chuman, 2015). The land reclamation process after coal mining is divided into four phases (Fig. 5)

The soil in mine reclamation areas has become a major focus of academic research in recent years. For example, in the Huainan coal mine reclamation, Yao et al. (2010) demonstrated that the soil had experienced various levels of heavy metal pollution. Also, a study from a specific reclamation region in China by Yang et al. (2011) showed that heavy metals such as Ni, Cr, Hg, and Cd in coal gangue can transfer to the upper covering soil, resulting in varying levels of soil contamination. According to Niu et al. (2017), the levels of Pb, Ni, and Cr in the reclaimed soil were found to be significantly higher than the background value in a restored coal mine land, from China.

Afforestation

Reforestation of mine land is founded on the ecological restoration concept, which is a comprehensive

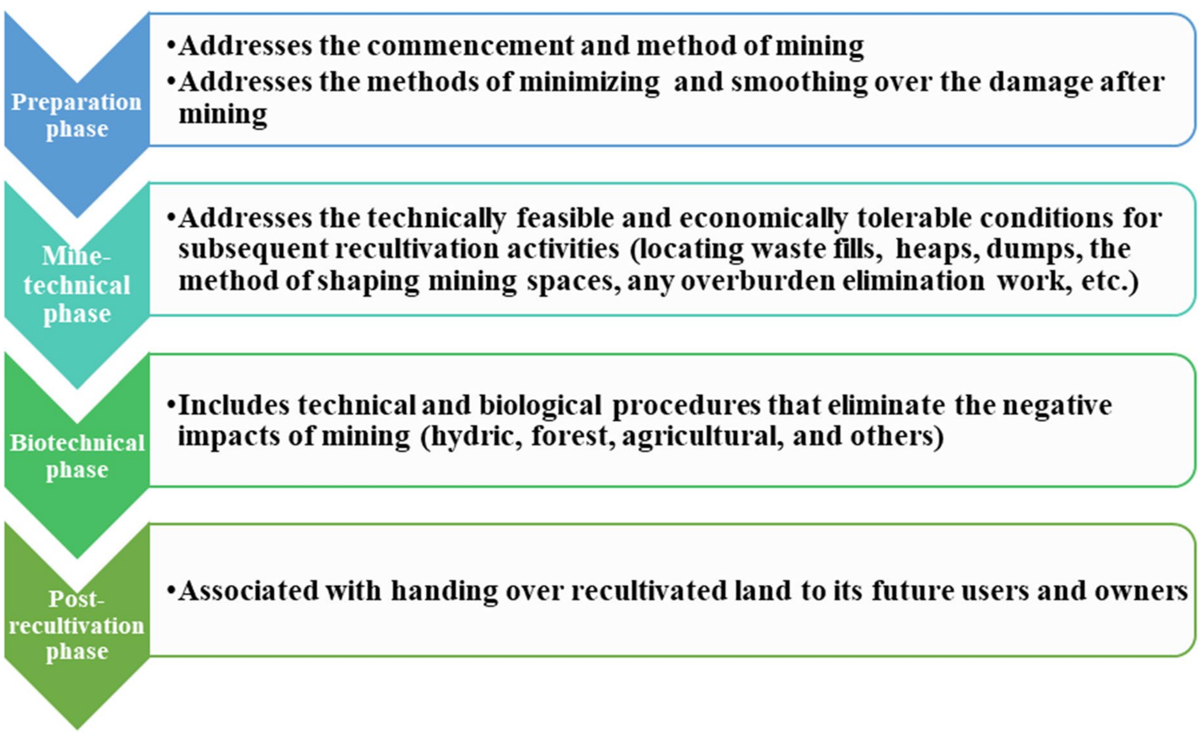

Fig. 5 Four phases of land reclamation after coal mining (Adopted from: Vrablikova et al. (2016))

strategy to the prolonged procedure of restoring mine-degraded land. This concept takes into account all of the basic physical, chemical, and biological features that the environment must have in order to be accepted as restored. Therefore, ecological restoration stages consist of a complicated blend of technical and biological processes, with the capability of restoring a site to conditions similar to those that existed before mining took place (Maiti & Ahirwal, 2019; Shojaee Barjoee et al., 2023). The understanding of how different tree species adapt to reclaimed mine soil is highly associated with the planning of reforestation and efforts toward sustainable forest management (Macdonald et al., 2015).

Plants can have direct and indirect impacts on the soil by the ways in which they affect the biotic community of the soil, which in turn can have an impact on the plant growth and formation of soil (Frouz et al., 2008). The plant–soil biota interaction can be broadly categorized into two primary pathways, namely, the root-associated pathway and the litter-associated pathway (Wardle et al., 2004). The interaction between soil biota and plant roots can immediately impact plant performance since the biota directly engages with the living components of the plant. Plants distribute a major part of their photosynthetic absorptions toward their rhizosphere symbionts and root, including N-fixing organisms and mycorrhizal fungi (Smith & Read, 2008). Several factors affect the level of benefit to the plant from these symbionts notably the soil's developmental stage. For instance, in the early and intermediate stages of succession, when N is limited, N fixation is beneficial. However, once sufficient N has been collected in the ecosystem, the N-fixation costs will surpass the benefits (Vitousek & Field, 1999; Menge et al., 2012).

The effects of plant litter on release of nutrients and topsoil development constitute another group of interactions (Laughlin et al., 2015; Ponge, 2013). Dead aboveground plant biomass, in the form of litter, constitutes a significant contributor to carbon and nutrient entry into the soil. The above-mentioned interactions play a crucial role in the process of soil formation, especially in post-mining areas where one can identify distinct variations in soil development depending on the plant species that are cultivated on the same substrate (Frouz et al., 2013). It has been proven that in contrast to plants using conservative procedures for growth, fast-growing plants having thin leaves generate nutrient-rich litter that releases more nutrients and degrades more quickly (Cornwell et al., 2008). However, the quality of the litter has additional impacts on the soil food web apart from its direct effects on degradation and nutrient release. Rates of nutrient release and the degradation of organic matter are determined by the soil biota. Bacteria-dominated food webs featuring fast organic matter mineralization and nutrient release are promoted by fast-growing plant litter. On the other hand, conservative plant litter boosts food webs dominated by fungi featuring a slower rate of nutrient release and organic matter turnover (Ponge, 2013). In addition to this immediate impact on nutrient release, litter quality also significantly influences the topsoil's physical structure, either through direct or indirect effects on the composition of the soil food web (Ponge, 2003).

Hence, afforestation is a typical method employed for the restoration of degraded lands (Fig. 6). The process of tree growth facilitates the enhancement of soil-forming mechanisms, thereby assisting in the formation of organic matter and the growth of microbial and microfaunal communities (Merilä et al., 2010; Lamb et al., 2011). Different plant species are distinct in terms of the organic matter amount they provide to the soil, and the rate of C sources in roots or litter is species-specific (Finér et al., 2007). Additionally, different species of trees may have distinct effects on the chemical characteristics of the soil, including the pH or the proportionate amount and chemical composition of macronutrients (Hagen-Thorn et al., 2004; Iovieno et al., 2010). For instance, tree species such

Fig. 6 Forest reclamation in the Sokolov district (*Source* O. Mudrak)

as *Alnus spp*. can enhance the N content of the topsoil by promoting N-fixation and producing an N-rich litter (Ekblad & HussDanell, 1995). The impact of trees on the composition and extent of vegetation in the understory layers is primarily attributed to their impact on the formation of soil and other soil organisms, such as invertebrates (Frouz et al., 2008; Mudrák et al., 2010). The procedure of forestry reclamation has predominantly focused on the establishment of monoculture stands. However, in cases of technical reclamation, non-native tree species and shrubs are sometimes utilized, despite their potential for invasiveness, rendering them unsuitable (Brown & Swab, 2021; Pergl et al., 2016). A successional area is vulnerable to invasion if the source of diaspores from an invasive species is nearby (Řehounková & Prach, 2008). These kinds of species can have a detrimental effect on biodiversity owing to their allelopathic properties and impact on soil chemistry (Vachova et al. 2022).

The Sokolov post-mining region has undergone significant reclamation efforts, resulting in the afforestation of large areas of land with a wide variety of tree species. The young trees have been planted directly into the slightly alkaline (pH 8–9) overburden, which is made up of cypress clays (Frouz et al., 2008). In this area, many investigations have been conducted to assess the physicochemical properties of soil after reclamation. For example, in an area planted by different tree species including spruce, oak, and alder, Jačka et al. (2021) found that the alder stand was having the highest percentage of earthworms, macropores, infiltration capacity, organic/humus layer, field-saturated hydraulic conductivity, and horizontal preferential flow in topsoil. In addition, at the oak stand, mineral subsoil had the highest horizontal range and substantial preferential flow within strong roots. On the other hand, the spruce stand, where water flow was partly stopped in the fermentation layer, had the lowest infiltration capacity, preferential flow size, and earthworm number. In the same site, Kaneda et al. (2020) also indicated that in the soil Olsen phosphorus reached the highest level in the middle successional stage, whereas extractable organic carbon, extractable organic N, and inorganic N all elevated with expanding succession. Another study in the Sokolov mining basin by Spasić et al. (2020) indicated that with regard to physical and chemical characteristics, broadleaf tree species such as lime (*Tilia cordata*), pear (*Pyrus communis*), Scots elm (*Ulmus glabra*), and maples (*Acer pseudoplatanus* and *Acer platanoides*) are the most appropriate species for soil development on lignite restored mine sites. Sun et al. (2019) also reported that in young soils from post-mining sites in Sokolov, N fertilization can boost plant development. However, residual inorganic N and growing N_2 fixing plants not only have substantially fewer advantages but also even have detrimental impacts on plant-soil feedback and plant growth.

In a study on two forested post-coal mining sites with *Alnus glutinosa* and *Alnus incana* near Sokolov, Frouz and Bujalský (2018) showed that poor soil ventilation can enhance soil CO_2 concentration sufficiently to restrict microbial respiration, which considerably enhances variation in the interaction among CO_2 flow from soil and soil CO_2 concentration. Also, from an area near Sokolov town, Bartuška et al. (2015) reported that compared to unreclaimed areas, restored sites (by planting alder) showed a faster accumulation of particulate organic carbon (POC). Although microbial communities in unreclaimed soils have been strongly associated with the light fraction of POC found between soil aggregates, microbial communities in restored areas were more closely related to POC bound inside of aggregates. From this study area, Bujalský et al. (2014) also revealed that there was a rise in soil respiration within the reclaimed sites when the site age moved forward up to 30 years, followed by a subsequent decline. When compared to reclaimed alder plantations of comparable ages, respiration at unreclaimed sites elevated with age and was normally lower. In another study on this site, Bartuska & Frouz, (2015), found that the C and N storage rates reduced with site age, potentially due to a decrease in litter input, while P content in soil was reduced with site age, probably due to leaching and plant uptake. Obviously, the soil pH tendency to decline in alkaline soils and rise in acidic soils is caused by the accumulation of C and N with site age.

From a study on post-mining afforested soils near Sokolov, Šnajdr et al. (2013) demonstrated that the rates of microbial degradation processes, either in the soil or the litter, are significantly influenced by the dominating tree vegetation. Additionally, microbial biomass and enzyme activities were comparable between spontaneous succession and revegetated areas, with the exception of the increased activity of enzymes at revegetated areas with Alnus, suggesting that the two types of areas developed their soils at the same rates. In an earlier study on a reclaimed site with alder species (*Alnus glutinosa, A. incana*) near Sokolov, Šourková et al. (2005) found that the accumulation of organic C and discharge of organic acid into the soils are the reason for the reduction in soil pH that happens with increasing revegetation age. Furthermore, they conclude that restored soils have been partially stabilized in terms of soil faunal communities, soil C, nutrient cycling processes, development of forest floor, and vegetation cover and composition. Another study on this site by Háněl, (2002), revealed that nematode communities became more diverse and extensive with a notably higher percentage of plant parasites and omnivores.

In the Velká Podkrušnohorská spoil heap, Kaneda et al. (2013) discovered that when litter has been added to soil, the available organic matter resulted in an elevation in the respiratory level that exceeded the combined levels of original litter and soil respiration, indicating the priming impact. While adding excrement to soil did not yield any similar increase, most likely due to the easily available organic matter. From North Bohemia, Hendrychová et al. (2012) reported that the impact of soil characteristics on the species richness of invertebrates in post-mining regions and stands that have undergone forest reclamation for several decades has been observed. In an earlier study from the same study area, Remeš and Šíša, (2007), revealed that the black alder plantation appears to be advantageous in the initial phase of forest reclamation, both in terms of the rapid development of vegetation cover on reclamation fields and the process of soil forming and treatment.

The earthworm's presence and litter chemistry of the planted trees have both been demonstrated to have significant impacts on the development of soil (Frouz et al., 2013; Hlava et al. 2014; Walmsley et al., 2019). Given that they can modify their environment, earthworms are an essential part of the soil fauna and are considered ecosystem engineers (Blouin et al., 2013). In this regard, there are many studies assessing the impact of earthworms on soil. For example, in Sokolov brown-coal mining district reclaimed by larch, oak, and alder, Walmsley et al. (2019) found that planting trees having easily degradable litter may facilitate the formation of soil via supporting enormous numbers of soil fauna, particularly earthworms, which generate humus. In addition, they conclude that alder plantings provided the lowest ratio of C/N and the most palatable litter, consequently supporting the biggest populations of soil macrofauna. This, in turn, impacted the soil compaction and thickness of the humus layer in the surface layers.

Similarly, from a naturally revegetated post-mining area in the Sokolov, Frouz et al. (2006) reported that C mineralization was not considerably enhanced by soil macrofauna access, but organic matter emission into the mineral layer was enhanced. This impact was more noticeable on the reclaimed site. They also found that the increase in microbial respiration and biomass, as well as enhanced water retention in the soil, can be attributed to the organic matter accumulation in the mineral layer. Another study by Frouz et al. (2013) on afforested post-mining sites near Sokolov City showed that the presence of soil fauna in forested spoil heaps has a significant impact on the structure of the top layer of soil. In this study, the biggest quantity of organic materials has been found in litter and the Oe horizon when soil fauna was limited, while in the presence of a significant amount of soil fauna most organic matter has been absorbed into the A horizon, which is primarily mineralized.

Agricultural reclamation

The primary aim of agricultural reclamation is to restore highly fertile soils that are crucial for the production of many kinds of food, forage, or feedstock crops. This encompasses the revitalization of productive croplands, pastures, and rangelands. Post-mining agriculture initially focuses on the development of soil functions and unstable structures on humus-poor raw soils which support initial ecosystems. The initial crop yields are relatively low, likely owing to insufficient nutrients and limited biological activity, and therefore might not accurately indicate the full potential for crop production (Knoche et al., 2019). The process of agricultural reclamation consists of various activities such as soil preparation, application of organic and inorganic fertilizers, and cultivation of cereal crops in cases where the intended land use is for arable purposes. Alternatively, grass mixtures may be sown to create a permanent grassland. The pedological evaluation forms the foundation of agricultural reclamation projects (Leitgeb et al., 2014).

Certain crops, such as alfalfa, are able to break through densely compacted soils despite their high penetration resistance. Growing alfalfa in compacted soils has been the subject of extensive studies due to its ability to improve infiltration rate and hydraulic conductivity (e.g., Meek et al., 1992). The reported condition can be attributed to three factors: (i) root channel formations, (ii) potential gradients surrounding the roots are increased because of water absorption by roots, which then leads to particle rearrangement and forming of cracks, and (iii) due to root exudates, resulting in aggregation of soil (Angers & Caron, 1998; Horn et al., 1994). Furthermore, it has been found that some annual crops with high energy and platform productivity, such as sorghum, Sudan grass, or miscanthus, have the potential to be more effectively integrated into disturbed land without jeopardizing the development of soil (Knoche et al., 2019). In order to improve the development of soil structure, Krümmelbein and Raab (2012) suggested employing deep-rooted and perennial crops and minimizing tillage. Minimal tillage, as demonstrated by Arshad et al. (1999), increases steady-state infiltration without significantly changing bulk density. According to McGarry et al. (2000), there was a notable increase in cumulative infiltration and rates of infiltration in areas where no-till farming was implemented in comparison with traditionally tilled sites. This was attributed to the presence of roundish pore forms and a greater pore continuity, which were identified by conducting image analysis.

When comparing the effects of agricultural and forestry reclamation on earthworm ecological groups and individual species in Most region, Hlava et al. (2014) found that under standardized soil characteristics, alterations in earthworm populations throughout the succession were greater in the agricultural reclamation process. From the agricultural reclaimed post-mining area in the Podkrušnohorská dump (northwestern part of the Czech Republic), Bodlák et al. (2012) revealed a statistically strong correlation between soil organic carbon and fundamental pedological parameters. In a study around Ostrava city, García-Sánchez et al. (2018) reported that the bioconversion and translocation factors did not reveal the significant potential of maize plants to extract PAHs.

Application of topsoil layer

The term "topsoil" refers to the A (or A and part of B) layers of meadow and forest soils as well as the tilled portion of farmland which is mainly saved before a mining activity and can be employed for reclamation. Generally, depending on the degree of soil disturbance, various methods have been developed for transferring topsoil (Frouz, 2021). A notable method for the application of topsoil involves the use of complete and uninterrupted soil blocks. These blocks are extracted from a donor area, and along with reconstruction at the destination land, it focuses on maintaining a similar form. Whole-ecosystem transfer is an alternate term for this method (Good et al., 1999; Waterhouse et al., 2014). The transfer of intact soil monoliths is a method of soil transfer that is characterized by its gentle nature. Moreover, the topsoil application is kept in stockpiles for an extended period of time, and subsequent vast grading leads to insignificant soil disturbance, loss of soil aggregates, and soil organic matter (Frouz, 2021). Applying topsoil has the immediate advantage of improving the conditions of the soil in the desired area (Bořůvka et al., 2012). When a seminatural or natural area is applied as a topsoil source, the resultant topsoil can serve as a significant reservoir of soil biota and plant propagules. This is specifically evident when the soil is directly transferred without being stored in a stockpile before applying it (Boyer et al., 2011).

If the plant propagule sources are natural habitats, then a method comparable to the whole ecosystem transfer, known as the direct transfer of sod or just direct topsoil, could be useful in recreating those ecosystems at the donor site. This method has the same benefits as soil block transfers considering that soil biota plants, and soil, are all transmitted at the same time. The most important difference between these two methods is the fact the soil is managed considerably less carefully during the direct transmission of topsoil or sod, which results in much lower costs than whole soil block transfer. For optimal success, it is recommended that direct transfers are carried out during the most suitable season of the year to ensure that the donated soil material is not subjected to excessive erosion and remains sufficiently moist (Frouz, 2021). It is common practice, however, to save topsoil and store it in stockpiles for a certain amount of time, generally for years, before using it in reclaiming activities. Soil biota and seedbanks can be damaged by the anaerobic and compacted conditions that develop in soil stockpiles (Boyer et al., 2011; Harris et al., 1989). It is possible for stockpiles to experience an overgrowth of weeds, leading to a process known as ruderalization. This process has the potential to enhance the seedbank of undesired species. Given these problems, it is generally considered that soils that have been stockpiled are lower-quality sources of soil biota and plant propagules in comparison with soil that has been directly transferred. In spite of this, using stockpiled soil in reclamation activities immediately improves the condition of soil (Frouz, 2021).

Since transporting and spreading of topsoil include several entries of heavy machinery, compaction is a significant issue with all types of topsoil applications. If the transferred topsoil contains an excessive amount of clay, compaction even becomes a more severe issue and could possibly impede plant growth. This is especially challenging for forest reclamation. The generation of discontinuity layers, which can restrict the natural flow of water within the soil profile and lead to gelification, can be attributed to compaction or the utilization of layers that are not naturally compatible. The creation of such water-impermeable layers can lead to erosion issues and, in extreme cases, to the development of landslides and detachment layers (Frouz, 2021).

In a study of two reclaimed brown-coal mining dumpsites by topsoil application in Northern Bohemia, Borůvka et al. (2012) reported that the humus quality and organic carbon content of the soil, which are often poor in the dumpsite soils of the investigated area, were shown to rise by using natural topsoil cover. The quantity of available phosphorus, which is also mainly inadequate in these soils, was also slightly raised. On the other hand, the available calcium and magnesium contents were decreased in the covered areas, yet it was still extremely high. Additionally, natural topsoil cover also contributed to a reduction in the quantity of clay, whereas both the total and the capillary porosity of the soil were reduced. Milan et al. (2006) also showed that the content of PTEs in the reclaimed soils by topsoil application was within range of the levels prevalent in the natural soils and in some cases were even lower.

Conclusion and future perspectives

Coal mining has been one of the most significant environmental concerns due to its vast quantities of metal dust generated during coal extraction, spoil disposal, overburden soil, and transportation in the areas nearby mines. The complete degradation of soil resulting from these activities is one of their most significant environmental effects. Both physical and chemical processes contribute to soil degradation. Physical processes impact the structure, particle size, depth, and compaction state of the soil, while chemical processes are driven by the characteristics of the soil that are associated with its chemical components and their interactions. Physical and chemical processes have detrimental impacts on soil health in both space and time, including erosion, salinity, soil toxicity, and water loss. Once coal mining has ended, the impacted region is required to be reclaimed in an attempt to mitigate the adverse impacts of the operation, albeit restoration strategies can differ depending on a variety of factors and trends. The majority of mine wastes that are technically reclaimed have been transformed into either agricultural lands or forests in the Czech Republic. The ecological characteristics of some older post-mining sites that have undergone spontaneous successions, including soil water-holding capacity, biomass production, and soil development, were often similar to those of technically restored areas. As a result of their geodiversity, young successional sites, on the other hand, support a significant degree of biodiversity. Nevertheless, despite its potential, spontaneous succession has only occasionally been employed as a strategy for ecosystem recovery, mostly due to its limited predictability. To date, the Sokolov mining district has been the focus of the majority of the comprehensive studies from the Czech Republic region, while other coal mining areas in this country received not enough attention. The majority of studies conducted to date on reclaimed and unreclaimed mine sites in Czechia have not sufficiently addressed the human health and ecological risks through the assessment of organic and inorganic pollutants instead referred to alterations and developments in the soils' biological, chemical, and physical characteristics of the topsoil layers. Thus, there are significant research gaps in studying coal mining areas in the Czech Republic which should consider in future studies, including:

- In the Czech Republic, there is a lack of research on the various environmental factors that have an impact on mining soils. Consequently, the lack of environmental heterogeneity comparisons makes it difficult to effectively demonstrate the potential distribution of pollution, determine the degree of pollution, or analyze and evaluate the pollution risk from PTEs in coal mining. Therefore, for future studies, it is recommended to consider these issues.
- In the Czech Republic, information on the impact of agricultural restoration and topsoil application strategies in coal mine soils is extremely limited. The findings of an extended study in the coal mining areas may address this knowledge gap.
- Coal mining can impact soil physicochemical characteristics and decrease soil nutrient contents in and surrounding the mining field, and this has been shown to be an important tool for measuring soil health in earlier studies. Thus, monitoring soil properties, including soil fertility, is important for land rehabilitation and management.
- Planning and management of restoration methods can be improved by evaluating the environmental risks associated with coal mining activities. Yet, the majority of environmental risk evaluations in Czechia focused on a single mining location or current pollution status. By impacting the physical and chemical characteristics of the soil and the migration of PTEs, environmental factors can potentially have an effect on potential ecological hazards. To thoroughly evaluate the past, present, and predicted future of mining sites, it is, therefore, necessary in the future to combine the ecological cumulative impact.
- Ecological reclamation and assessments in mining sites can be supported by accurately determining the range of disturbances by mining activities. Earlier investigations, on the other hand, largely concentrated their attention on the interior parts of mines. The range of disruptions resulting from coal mining activities should therefore be identified for future studies using a broad range of approaches.
- Recently, a study showed high content of microplastics in coal mine areas. However, there is a knowledge gap in this field of study worldwide and the Czech Republic is no exception. Future studies should therefore aim at providing a thorough investigation of the extent, origins, and features of microplastics and other emerging pollutants in the Czech Republic's coal mine area.
- Several investigations have been conducted all over the world to assess the PTEs pollution of reclaimed fields in coal mining areas by comparing the level of HMs with local background levels. But the accumulation of PTEs in plants and the potential impacts of PTEs in the reclaimed soil on the plants have not yet been thoroughly addressed in the Czech Republic and worldwide coal mining regions. Thus, it is required to conduct extensive studies in order to fully understand the mentioned impacts on plants in reclaimed and unreclaimed coal mining areas not only in the Czech Republic but also on a global scale.
- Earlier studies have shown that biochar can improve the physical, chemical, and biological characteristics of soil and enhance the bioavailability of vital nutrients in coal mining areas. Since this issue has not been getting attention in the Czech Republic, for future studies it is vital to find an efficient modified biochar for remediating polluted soils by coal mining activities.

Author contribution AR helped in conceptualization, methodology, investigation, visualization, writing—original draft, writing—review & editing. MZG and MH contributed to conceptualization, writing—review & editing. All authors reviewed the results and approved the final version of the manuscript.

Funding No funding was received for conducting this study.

Data availability The datasets generated during this study are presented in the tables in this manuscript and in the supplementary material.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Consent to participate Not applicable.

Consent to publish Not applicable.

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