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Review

An Overview of Carbon Footprint of Coal Mining to Curtail Greenhouse Gas Emissions

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Abstract: Despite the trend of a transition to "clean" energy, the coal industry still plays a significant role in the global economy. The constant need for raw materials and energy for production leads to an environmental crisis—an increase in the content of greenhouse gases in the atmosphere, especially in the mining regions. The purpose of this study was to analyze the impact of the carbon footprint on the environment and to study ways to reduce the negative impact of coal mining enterprises on the ecology. To analyze the chosen topic, the available reviews and research articles on the impact of the carbon footprint of coal mining enterprises, and the ways to reduce it and restore the biodiversity of wastelands, were used. It was found out that a complete ban on the extraction and use of coal in the industry will not lead to the desired result. The main ways to reduce the negative impact of coal mining enterprises on the environment were considered. The most promising direction for reducing the carbon footprint is the restoration of the vegetation cover by phytoremediation methods and the creation of carbon landfills in reclaimed territories in technogenically polluted coal mining regions.

Keywords: carbon footprint; coal mining enterprises; pollutants; land reclamation; biological remediation

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1. Introduction

Anthropogenic activities affect ecology, the state of the environment, and climate change, which negatively affects the health of the world population, reducing the healthy life expectancy, increasing mortality, worsening living conditions, and forming social injustice [1].

The increase in greenhouse gases, toxic emissions from anthropogenic activities, are among the main causes of environmental changes [2]. Since the XVIII century—since the beginning of the industrial revolution—there has been a sharp increase in the concentration of greenhouse gases in the atmosphere and the average global temperature of the Earth [3], which is associated with the discovery and use of fossil fuels as the main source of energy. The natural greenhouse effect created the environment necessary for the formation and preservation of life on the planet, but its increase leads to a violation of the balance of ecosystem processes, both at the regional and global levels [4–6].

The totality of all greenhouse gas emissions produced directly or indirectly as a result of human activity is commonly referred to as the carbon footprint [7,8]. The carbon footprint is expressed in the carbon dioxide equivalent (CO_2e). It is considered to be the equivalent of carbon dioxide by multiplying the mass of a specific greenhouse gas by its global warming potential [9,10]. Different countries (Great Britain, the USA, France, etc.) and different international organizations (the UN, the World Resources Institute, the International Organization for Standardization, the World Bank, etc.) have different approaches to calculating the carbon footprint [11–14], but the goal is the same—to reduce the negative impact of greenhouse gases.

The fight against emissions of greenhouse gases and other substances polluting the environment began actively at the end of the XX century [15]. In 2005, the Protocol on Greenhouse Gas Emissions (Kyoto Protocol) entered into force, the main purpose of which was to stabilize the concentration of greenhouse gases (GHG) at a level that excludes the dangerous anthropogenic impact on the planet's climate. The protocol establishes a quota for GHG emissions [16,17]. In 2015, the Paris Agreement was signed, which established a new mechanism for international climate management after 2020 and set a goal to control the increase in the global temperature by no more than 2 °C and strive to ensure that it does not exceed 1.5 °C in order to protect the ecological safety of the Earth. However, the global response to climate change still requires urgent assistance, and the targets for the expected nationally determined contribution set by each country are far from reality [18]. There is an extremely large gap in the indicators for air pollutants in developed countries and Russia. Thus, specific emissions of sulfur oxides, which lead to acid rain and the degradation of large areas of forests and lands, are 20 times higher in the country than in Japan and Norway and about 6–7 times higher than in Germany and France [19].

Climate change has many health consequences for people around the world. There are three ways in which climate change affects human health. These are changes in weather conditions (heat, drought, heavy rains, etc.); the spread of diseases (vector-borne, water, and food); and social unrest (hunger, inequality, conflicts, etc.) [20]. Thus, the increase in GHG emissions is considered as the cause of infectious and non-communicable diseases, negative consequences for nutrition, water security, and other social upheavals [21].

It is believed that electric power production enterprises and transport are the main sources of GHG emissions (sulfur dioxide, nitrous oxide, methane, sulfur hexafluoride, hydrofluorocarbons, perfluorocarbons, etc.). Thus, coal-fired power plants account for about 20% of such emissions. Even deforestation and other changes in land use lead to the release of carbon dioxide and methane into the atmosphere [22]. Methane emissions are the main factor in increasing the concentration of greenhouse gases. It is known that about 33% of anthropogenic methane emissions occur during the extraction and transportation of fuel [23]. Coal mines are one of the largest sources of anthropogenic methane emissions [24]. Coal mining releases methane trapped in the coal and surrounding formations. The US Environmental Protection Agency has predicted [25] that by 2030, global methane emissions from coal mines around the world will exceed 784.3 $MtCO_2e$. China will account for more than 55% of the total, followed by the United States (~10%), Russia (~7%), Australia (~5%), Ukraine, India, and Kazakhstan (~3–4% each).

The changes in global emissions are mainly caused by changes in the use of coal, while the growth in the use of oil and gas has not weakened since 1980 after the oil crises of the 1970s. Coal mining, processing enterprises, and the use of coal as fuel are among the sources of greenhouse gases that simultaneously pollute the environment with coal dust, emit toxic elements into groundwater, etc. [26,27]. Many analysts suggest that the use of coal may have reached its peak. The decline in the use of coal in the countries of the Organization for Economic Cooperation and Development (OECD) has decreased by 25% over the past decade. Thus, in 2020, the global coal production and consumption decreased due to COVID-19 [28]. But, in 2021, there was an increase in this indicator worldwide. In 2022, the EU countries almost completely reduced the consumption of Russian coal but increased the consumption of their brown coal, which is less environmentally friendly in all aspects [29,30]. The growth of coal consumption in countries outside the OECD remains high. The global peak of coal use largely depends on China, which accounts for 50% of the global use of this raw material [31]. According to forecasts, China's economic and social development will depend on coal for about another ten years [28].

During the decade, a complete abandonment of fossil fuels, including hydrocarbons, as an energy source is unlikely, but the trend toward decarbonization is relevant and will continue, changing the economic structures of countries [32,33]. In addition to the transition to renewable energy sources, in order to reduce the negative impact of coal mining enterprises on the environment and preserve the health of the local population, the following measures are relevant: efficient coal mining, intelligent mine construction, the development and modernization of key technologies and equipment for efficient coal processing, underground gasification, intelligent and flexible coal-based electricity generation technology, electricity production technology based on a new energy cycle, the development of special coal-based fuels, bulk and special coal-based chemicals, energy conservation and a reduction in consumption, large-scale and inexpensive carbon capture, and the utilization and storage of CO_2 [18,34]. A special role is played by the measures for the reclamation of technogenically disturbed lands.

Thus, methane makes a significant part of greenhouse gases. Most of the methane is released into the atmosphere during the extraction, transportation, and processing of coal. Russia is on the list of countries with significant atmospheric pollution caused by the extraction and processing of hydrocarbons, including coal [35]. The Kemerovo Region–Kuzbass is an industrially developed territory, which is home to one of the largest coal mining areas in Russia and the world—the Kuznetsk Coal Basin. According to estimates for 2021, there are 163 active and 110 mines and open-pit mines under construction in the basin [36]. With the coal industry development, an increase in the share of open-pit coal, and the expansion of coal mining, the environmental situation and the health of the local population deteriorated, and social tensions and the threat of destruction of the natural landscapes in the region are growing. But, since 2022, a comprehensive scientific and technical program of the full innovation cycle "Clean Coal—Green Kuzbass", approved by the Government of the Russian Federation, has been launched. This program includes a new development strategy in which the industrial region should become an innovative platform for the advanced global and Russian experience projects in the development and implementation of technologies for the environmentally balanced management of coal mining operations based on a digital transformation, an integrated coal processing technology, and programs to improve the environmental safety of the region [37].

This study is aimed at assessing the current state of the coal industry, studying the degree of the environmental impact of coal mining enterprises through the carbon footprint, and considering possible ways to reduce the negative consequences arising from the extraction and use of coal.

2. Methodology

The literature search was launched in November 2021; it included the materials published in the period from 1 January 2011 to the present and was supplemented in October 2022 with a review of 2001–2010 publications. Databases of Scopus and Web of Sciences articles were used for cross-checks. The literature review and analysis were based on the topic of the carbon footprint of coal mining enterprises and ways to reduce it and restore the biodiversity of waste lands. Also, individual articles discussing the relevance of the topic, understanding the properties and mechanisms of the carbon footprint, determining promising research areas in this area in English and Russian were considered. To reduce the number of sources, only articles and reviews were considered; conference materials and other types of publications were removed from the review. We used a search strategy based on several queries; the final ones were selected after several search passes by a qualitative assessment of the number of results obtained and their relevance. The entire bibliography of the included studies was manually checked for compliance with the subject of the search by title and abstract. After excluding overlaps across all search databases, 328 sources remained under consideration.

3. Coal Mining Industry

The main coal mining countries of the world include China, the USA, India, Australia, and Russia [38]. There are known coal reserves (Figure 1) on all continents, except Antarctica, which are not evenly distributed, with the highest concentration in the northern hemisphere [39,40]. But 90% of the world's coal reserves are concentrated in 10 countries (the USA, Russia, Australia, China, India, Indonesia, Germany, Ukraine, Poland, and Kazakhstan). Table 1 shows the main 15 exporters [41] and the main importers [42], respectively, 98.8 and 85.5% of the global coal purchases for 2021. The main consumers of black coal are China, the USA, India, South Africa, Ukraine, Poland, and Russia, and for brown coal—Germany, China, Russia, and the USA. It is believed that the size of the global coal production is approximately equal to its global consumption [38].

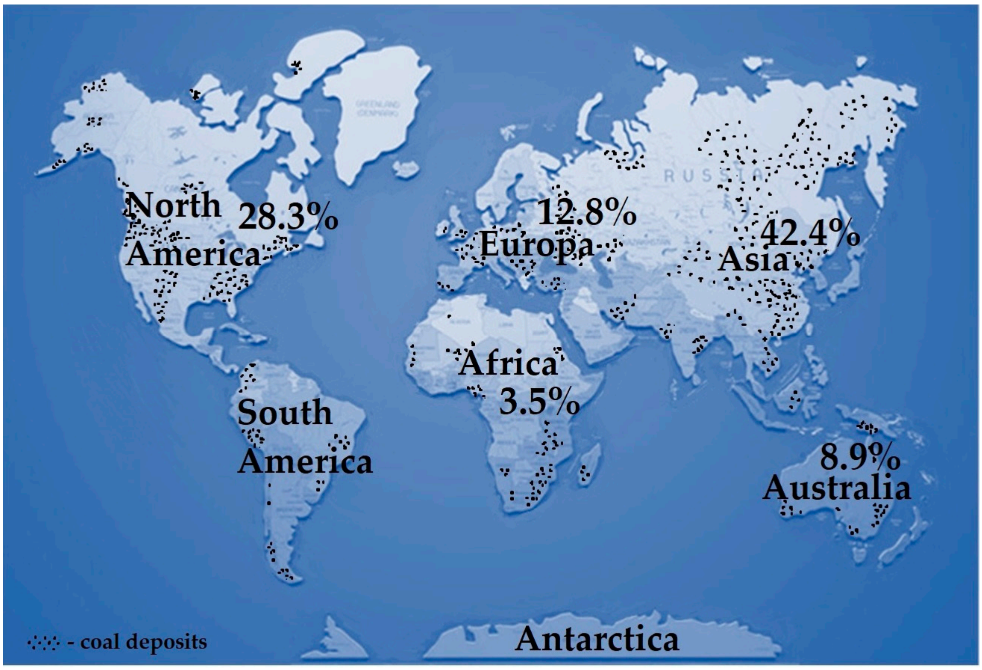

Figure 1. Distribution of coal reserves by continents.

Table 1. Main global coal exporters/importers (2021).

Countries	Export		Countries	Import	
	% of Total Exports	**Cost, Billion USD**		**% of Total Imports**	**Cost, Billion USD**
Australia	35.7	43.90	India	17.3	25.7
Indonesia	21.6	26.50	Japan	16.9	25.2
Russia	14.3	17.60	China	15.3	22.9
United States	7.9	9.70	South Korea	9.7	14.5
South Africa	4.9	6.08	Taiwan	5.5	8.2
Canada	4.9	6.05	Germany	3.5	5.2
Colombia	3.6	4.40	Turkey	2.7	4.1
Mongolia	1.5	1.90	Malaysia	2.7	4
Mozambique	0.9	1.10	Vietnam	2.1	3.2
Kazakhstan	0.8	0.93	Philippines	1.9	2.9
Netherlands	0.7	0.88	Brazil	1.9	2.8
Poland	0.7	0.83	Ukraine	1.6	2.4
Philippines	0.5	0.60	Pakistan	1.6	2.32
Mainland China	0.3	0.42	Indonesia	1.5	2.28
Vietnam	0.3	032	Netherlands	1.2	1.8
Other	1.2		Other	14.5	

According to [39,40].

3.1. Carbon Footprint of the Coal Industry Life Cycle

Due to the development of the economy, technology, and population growth, coal consumption is increasing, which damages the environment [43–45]. As the main link in coal consumption, coal mining plays an important role in the total carbon emissions generated by coal consumption [32]. With the continuous development of technologies, the process of underground coal mining is gradually being mechanized and transformed into a fully mechanized coal mining technology, which is currently widely used [46–48]. Nowadays, there are very few studies on carbon accounting for fully mechanized coal mines, and there is no accounting model to quantify the carbon emissions from each process in a fully mechanized longwall. It is necessary to analyze the sources of the carbon emissions at each stage of the mining process.

The main sources of CO_2 emissions from underground coal mining include energy use, GHG emissions, spontaneous combustion of coal, waste rock, and rough coal [49]. As a rule, fires in coal mines caused by spontaneous heating occur as a result of the slow oxidation in coal seams, in storage areas, or during transportation [50]. Spontaneous heating occurs when coal undergoes oxidation, the rate of which increases with an increasing temperature [51]. The gaseous products of the low-temperature oxidation of coal at the earliest stages are CO, CO_2, and H_2O. When the temperature rises, CH_4, H_2, and other low-molecular-weight hydrocarbons are released [52]. Some research has been conducted on the study of gas emissions from the spontaneous combustion of coal and their impact on the environment [53–56]. Many gases formed as a result of combustion are formed during conventional coal mining, but the concentrations of these gases vary depending on environmental changes, so there is no unified approach to assessing greenhouse gas emissions during coal oxidation.

Auxiliary elements are the sources of CO_2 emissions as well: drainage systems, ventilation systems, staff energy consumption per day, office space consumption, transport systems, etc. In open-pit coal mining, the following stages at which carbon dioxide emissions are generated must be taken into account: the open-pit coal mining area survey, the use of technical materials (concrete, steel, etc.), as well as appropriate machines (road builder, excavator, etc.). It is necessary to take into account the processes of crushing, loading, transporting, fixing the roof, and processing coal on site. All processes generate a large amount of carbon dioxide.

The use of machinery and the coal gas outlet are the main sources of carbon emissions considered for the mine. Spray-type pumping stations that consume electricity are widely used in the face to reduce the amount of dust; they produce GHG emissions. During underground coal mining, gases, mainly methane, leak out. The performance of blasting leads to some carbon emissions. The carbon emissions per ton of coal produced is 29.196 tons. Transportation accounts for 29% of the total carbon emissions from underground coal mining.

Coal enterprises need to use electricity through the secondary use of methane generated in the mine, as well as use this methane for various technological innovations.

3.2. Negative Impact of Enterprises Using Coal on the Environment

The Kyoto Protocol was the first global-level agreement dealing with climate change and reducing the impact of greenhouse gases on the environment. This document demonstrated how effective international cooperation can be in matters related to environmental threats. Thanks to the Protocol, alternative energy sources were actively introduced, and support was provided to developing countries in reducing greenhouse gas emissions. In 2014, it was recorded that as soon as the Kyoto Protocol entered into force, the level of greenhouse gases in the atmosphere decreased by 22.6% compared to 1990. Of course, such a result was achieved not only thanks to the Kyoto Protocol, but it played a significant role [57].

However, despite the efforts of the global community to reduce the carbon footprint, the negative impact of coal plants on the environment remains significant [58]. Coal plants pollute drinking water and groundwater [59]. So, around the coal mines in Moatize

(Republic of Mozambique), it was found that all the nearby rivers are polluted with arsenic (As), chromium (Cr), and manganese (Mn) during the monsoon season and As, Cr, Mn, lead (Pb), and nickel (Ni) during the dry season; the groundwater is polluted with Cr, Pb, and Mn. The presence of these elements negatively affects the health of the population [60].

The waste from coal-related enterprises is a serious problem for soils. Zhang [61] assessed the soil at the coal mining plant to determine six heavy metals (As, Pb, Cu, Zn, Mn, and Cd) and the potential environmental risk. The geoaccumulation index, the revised Nemerow Integrated Pollution Index (RNIPI), and the Potential Environmental Risk Index (RI) were used. The results showed that the Cd and As contamination was significant. The average values of Cd and As were 1.11 and 25.13 $mg \cdot kg^{-1}$, which was 42.55 and 4.41 times higher than its local background value. The geoaccumulation indices showed that the degree of the Cd contamination was strong, As average, and the state of the Cu, Pb, Zn, and Mn was uncontaminated. Xilinhot was heavily polluted based on the RNIPI and RI values. Accumulations of As, Pb, and Cd are mainly associated with anthropogenic sources, including coal mining and burning, as well as industrial exhaust emissions. Cu, Mn, and Zn were mainly obtained from the source material (natural sources). Mining changes the pH of the soil—the soil becomes either acidic or alkaline, which does not allow maintaining optimal conditions for the life of plants and some soil microbes. Soil microorganisms (fungi and bacteria) contribute to soil aggregation, improving plant growth. Microorganisms are in symbiotic relationships with plants, contributing to the assimilation of nitrogen and phosphorus by plants [59].

In addition to toxic substances, coal enterprises and coal-fired power plants emit radioactive contamination. The sources of the radiation emissions are volatile ash and coal itself, containing isotopes of uranium, thorium, ruthenium, and their decay products (for example, the most dangerous product of uranium decomposition is radon) [62]. Radioactive contamination is partially released into the atmosphere, getting into the soil, surface water, and food chain. Their presence in the environment changes the composition of materials, increasing the level of the natural background radiation. Even low levels of these isotopes pose a danger to human health because they accumulate in the body (for example, in the lungs), gradually enter the bloodstream, and are deposited in bones and teeth, remaining for life [63]. Open-pit mining contributes to local air pollution [64] with toxic compounds with documented genotoxic effects and an increased risk of cancer and cardiovascular and respiratory diseases of the local population [65].

The size distribution and chemical composition of coal dust particles are very complex. In the process of coal mining, both inhaled (diameter <0.1 mm) and inhaled particles (diameter <0.004 mm) are formed. Inhaled particles are those that enter the nose or mouth, and inhaled particles are the mass fraction of inhaled particles that penetrate the non-ciliated airways. Coal dust contains organic macerals and inorganic minerals (for example, quartz silica, phyllosilicates, and sulfides) [66,67], which can lead to damage to respiratory cells [68]. Due to their small size, inhaled coal dust particles can pass the filtration systems of the oral and nasal airways and be transported to the lower respiratory tract. Coal dust can come into contact with the vessels of the alveolar respiratory tract, the submucosa, and the cells of the epithelium of the alveoli [69]. Carbon particles can potentially overcome epithelial cells and capillaries and enter the blood vessels of the respiratory system. Inhaled coal dust can contribute to the inflammation of the alveolar epithelial cells and reduce the mucociliary clearance [70]. Inhaled particles from coal mines affect the overproduction of reactive oxygen species in the deeper airways, which eventually destroys the antioxidant system of the respiratory cell [71].

Prolonged occupational exposure, as well as a high concentration of coal dust and the toxicity of inhaled coal dust particles lead to various lung diseases in coal mine workers. Coal miners' pneumoconiosis, silicosis, chronic obstructive pulmonary disease (COPD), and mixed-dust pneumoconiosis are the most common respiratory diseases in coal mine workers [72]. Silicosis is a dangerous respiratory disease, mainly caused by respirable crystalline silica [73]. The published literature indicates that inhaled crystalline silicates are highly toxic and carcinogenic and cause cancer in lung tissues. It has also been documented that COPD and lung cancer occur due to the unprofessional exposure to open-pit coal mining [74].

China, African countries, Pakistan, India, and Russia suffer from carbon dioxide emissions [75,76]. Thus, the processes of the gasification and liquefaction of coal in China are the main sources of carbon dioxide. When using coal as a raw material for the production of chemicals, carbon dioxide emissions are more intense due to a higher carbon/hydrogen ratio compared to oil or natural gas [77,78]. For example, the emission factor of ammonia based on coal in China is 4.6 t CO_2/t NH_3, which is much higher than that of natural gas (2.1 t CO_2/t NH_3) and oil (3.3 t CO_2/t NH_3) [79]. In South Africa, coal is the predominant energy raw material [80]. Approximately 85% of the electricity generated is coal. As a result, South Africa is a major source of GHG emissions. Despite the phase-out of coal planned by 2040 as part of the global commitment to reduce greenhouse gas emissions, the transition to renewable energy sources in countries is difficult. This is due to the fact that coal is the cheapest source of fuel and that the use and consumption of solar, wind, and biomass energy has technical, financial, political (government inaction), and environmental problems [81]. For example, the production of biofuels damages food security, because it increases the competition for land use, water, and food [82]. In [83], it is described that the transition to wind energy is difficult, associated with the death of birds and bats, the noise load on the local population, and the need for a reliable network infrastructure, which is absent. The energy sources in Pakistan are mostly traditional (68–70%), such as oil, gas, and coal, and this country does not use renewable energy sources to overcome the energy crisis. Coal consumption in Pakistan increased by more than 100% from 2003 to 2008. Coal is mainly used in the brick industry, which is also a source of GHG emissions [84]. Pakistan is a coal-rich country and continues to invest in coal-fired power plants in order to provide a large amount of energy from coal in the future [85]. As Pakistan faces problems at hydroelectric power plants, switching to oil or gas for energy is inevitable, which increases the amount of GHG emissions [86]. In India, the mining industry (in particular coal mining) is the key industry of the country [87]. Islam et al. [70] presented data that the capacity of the coal-based electricity production in India may increase from ~200 GW in 2018 to 300 GW by 2030, which raises concerns. About 75% of the electricity in India is generated by coal-fired power plants, which produce significant emissions of solid particles, sulfur dioxide, and nitrogen oxides into the air [88]. That is, coal mines and power plants create a huge burden on the environment. For example, they pollute the ground and surface waters and emit a large amount of cubic and fly ash, and hence heavy metals [87]. The Singrauli district in central India is one of the most polluted industrial areas in Asia and has an extremely high Comprehensive Environmental Pollution Index (CEPI) [87]. According to Cropper [88], approximately 112,000 deaths annually are associated with the existing and planned coal-fired power plants. This draws increased attention to the benefits of switching from coal to renewable energy sources.

Enterprises using coal contribute to carbon dioxide emissions. The increased level of carbon dioxide affects the increase in the average global temperature of the Earth; the health of the population; and flora. Since 1906, the temperature has increased by 1.1 °C, and the current level of carbon dioxide in the environment currently exceeds 400 mmol/mol. According to forecasts, with a concentration of carbon dioxide in the atmosphere of about 670 mmol/mol, the temperature of the planet will increase by 1.4–3.1 °C, which will change the climate [4,15]. Indoor air quality is crucial for public health; in industrialized countries, people spend 80–90% of their time indoors, while vulnerable groups of the population (including the elderly and frail) often spend whole days indoors [89]. An increase in the concentration of CO_2 in the atmosphere leads to inflammation, a decrease in cognitive abilities of a higher level, bone demineralization, kidney calcification, oxidative stress, and endothelial dysfunction [90]. Carbon dioxide is the main substrate for photosynthesis. Almost 90% of known plant species belong to the biochemical-type C3. It is possible to increase the photosynthesis and biomass of these species in conditions of increased carbon dioxide content [91], although the growth and morphology of plants cannot be fully explained by the direct effect of carbon dioxide, only by photosynthesis, respiration, and water use [92].

The main wastes of the coal industry are stored in rock dumps, sludge settling tanks, and silt accumulators, which emit toxic fumes, dust, and combustion gases; during rains and floods, they pollute the water pool, soils, etc. [93]. Coal dust and residues are among the main sources of air pollution [94]. The main causes of dust emissions during coal mining and processing are drilling, blasting, loading, unloading, and transportation [95]. Dust emissions lead to a deterioration in air circulation and a decrease in its quality, visibility [96], climate change, and other environmental/ecological problems [97]. Exposure to coal dust leads to serious health problems [98]. Recently, the study of atmospheric pollution by coal dust and related potential harmful elements has become the main focus of environmental research [99].

Health problems caused by dust particles include silicosis and increased mortality. Coal dust particles get inside the human body through the ingestion of dust, inhalation, and absorption through the skin, as well as through the mouth through the consumption of contaminated food and water. Coal dust is considered a dangerous environmental pollutant due to its toxicity, persistence, and bioaccumulation ability. Toxic health effects include hypertension, headache, irritability, abdominal pain, nerve damage, skeletal problems, lung, liver and kidney problems, anemia, mental retardation, fatal cardiac arrest, and carcinogenesis [100].

Dust emissions from mining act as a trigger factor for respiratory diseases and can lead to various diseases among workers and people living in the vicinity [101].

Ishtiaq and colleagues investigated the concentrations of potentially harmful elements in coal dust and assessed the human risk and health impacts near coal mining areas. For this purpose, dust samples were collected near various coal mines in Cherat (Pakistan) and analyzed for the concentration of harmful elements. Certain concentrations of these substances were evaluated to assess the health risk. The results showed that ingestion was the main route of entry. The individual chronic daily intake of potentially harmful substances (PHE) was higher than their respective permissible exposure limits established for oral exposure routes by the Agency for Toxic Substances and Disease Registry. The values of the chronic risk or health index were observed to be < 1 for all the PHE and in the order Pb > Cr > Cd > Ni > Cu > Co > Zn. The higher health index values for Pb, Cr, and Cd may be associated with various chronic health problems, as observed during the medical examination in this study. Thus, safety measures are needed to reduce the impact of coal dust on public health [102].

The increase in mining areas reduces the natural landscape (protected, agricultural territories) accordingly. Overpopulation (the world population is expected to increase by 2.3 billion people in the period from 2009 to 2050), together with the reduction in agricultural areas, exacerbates the problem of food production (utility, product safety, hunger, etc.). Thus, Li [103] found that in 79% of the studied vegetables and 67% of the grain grown near coal-fired power plants, the mercury content exceeds the PTWI food safety standards, which is an important threat to the health of the local population. The reduction in natural landscapes leads to the loss of the ecological and production functions of the soil. That is, the loss of life support of organisms, the regulation of moisture, gas, heat exchange in the biosphere, and the maintenance of biodiversity [104]. In other words, coal mining is one of the most dangerous industries in the world [26,105]. Mining refers to harmful working conditions, as it is characterized by a high risk of accidents (injuries and mortality); workers are exposed to physical, biological, chemical, psychological, and ergometric hazards [106,107]. That is, miners have a higher risk of developing occupational diseases, especially respiratory diseases [108], compared to other types of work. The risks of occupational diseases are not limited to underground miners but also extend to open-pit mining workers [107,109]. Therefore, the development of new and the modernization of existing measures aimed at reducing toxic, carcinogenic emissions from enterprises using coal is relevant.

4. Ecological State of Russia

The Russian Federation supports the desire of the world community to reduce anthropogenic greenhouse gas emissions. It was planned to reduce emissions by 25–30% by 2030 compared to the 1990 levels [110]. Certain achievements have already been reached. Russia is already a global leader in the development of innovative technologies for nuclear energy, which is confirmed by the World Nuclear Association (WNA) [111]. The country has achieved energy efficiency of the uranium enrichment process, fast-neutron reactor technologies, etc. [112]. However, in terms of the comprehensive reduction in the carbon footprint, not only nuclear energy requires significant actions to introduce new technological solutions (Table 2). Despite the absence of advanced technologies, the widespread use of hydrocarbons, and a significant amount of atmospheric pollution from stationary and non-stationary sources, Russia, according to data for 2019 [113], ranks only fourth with less than 5% of the total global GHG emissions into the atmosphere after China, the United States (a joint share of about 45%), and India.

Table 2. Dynamics of total greenhouse gas emissions in Russia [1,2] (million tons of CO_2e per year).

Greenhouse Gases, Million Tons	Years							The Indicator Share 2019 to 1990, %
	1990	2005	2008	2011	2014	2017	2019	
Carbon dioxide (CO_2)	2525.5	1524.8	1609.2	1648.1	1671.6	1647.0	1679.4	66
Methane (CH_4)	441.5	466.1	484.7	506.8	859.1	383.3	315.4	71
Nitrous oxide (N_2O)	139.3	104.2	111.2	117.0	90.2	86.4	84.2	60
Hydrofluorocarbons (HFC)	35.9	15.7	14.7	9.4	24.1	34.3	36.5	102
Perfluorocarbons (PFC)	15.1	4.7	3.7	2.5	3.1	3.2	2.5	17
Sulfur hexafluoride (SF6)	1.4	1.3	0.8	0.5	0.8	1.3	1.4	100
Total	3158.8	2116.8	2224.3	2284.3	2648.9	2155.5	2119.4	67

[1] Excluding land use, land use change, and forestry. [2] The national report of the Russian Federation on the inventory of anthropogenic emissions from sources and removals by sinks of greenhouse gases not regulated by the Montreal Protocol for 1990–2019 was prepared by Yu. A. Izrael Institute of Global Climate and Ecology (IGCE) [114].

The distribution of the emissions into the atmosphere by the regions (Figure 2) of Russia and by the types of economic activity (Table 3) is not uniform and not unambiguous. The Siberian Federal District accounts for the main share of emissions, also from mining, among which coal is second only to oil and gas.

In the Russian Federation, the Kemerovo region–Kuzbass (coking coals) and the Krasnoyarsk Territory (energy coals) are the main regions of extraction of useful hydrocarbons (coal). The share of Kuzbass in the total volume of coal exports from Russia, the third largest supplier of this fuel to the world market, is estimated at 65% (for 2020). That is, the coal industry is the basis of the region's economy [115].

Pollution is catastrophically high for all environmental objects, including water resources. The condition of the rivers in the area is assessed as dirty/polluted [118].

A rapid increase in the coal production volumes and the intensity of the mining development over the past 10 years has been noted, mainly due to the open method; respectively, the negative impact on natural ecosystems, which are characterized by a unique biodiversity, is growing [119]. In other words, most of the territory of Kuzbass is subject to a strong anthropogenic impact (Figure 3). The list of unfavorable factors currently affecting the coal industry as a whole is very extensive: the irreversible process of the destruction and degradation of the soils under industrial waste dumps during open-pit coal mining, the pollution of underground and surface waters, the atmospheric pollution by industrial emissions, the disappearance of natural flora and fauna, as well as a catastrophic threat to the health of people living in the region [120].

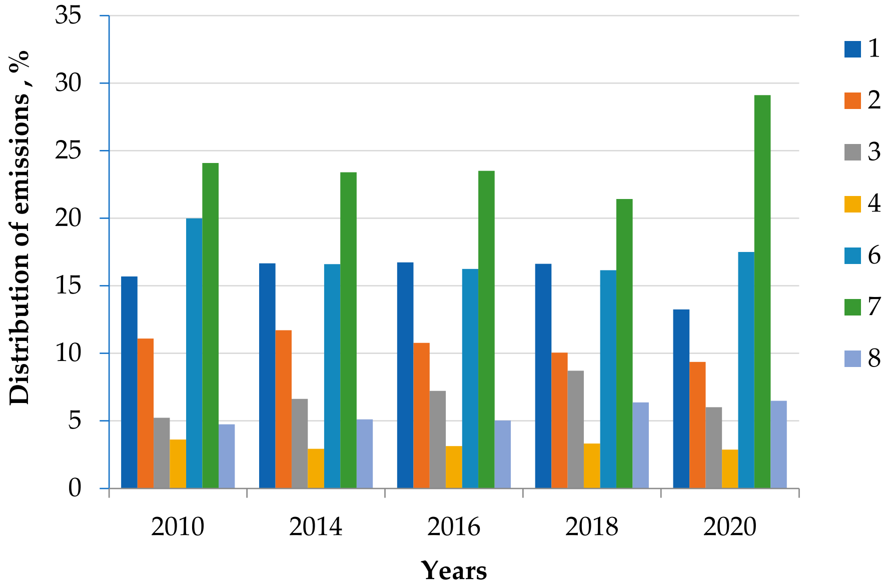

Figure 2. Dynamics of the distribution of emissions of air by regions of Russia pollutants from stationary and mobile sources (2010–2020): 1—Central Federal District; 2—Northwestern Federal District; 3—Southern Federal District; 4—North Caucasian Federal District; 5—Privolzhsky Federal District; 6—Ural Federal District; 7—Siberian Federal District; 8—Far Eastern Federal District. According to the Federal Service for Supervision of Natural Resources [114].

Table 3. Emissions of pollutants into the atmosphere from stationary sources by type of economic activity (2017–2021) *.

Types of Economic Activity	Share of Emissions, %				
	2017	2018	2019	2020	2021
Agriculture, forestry, hunting, fishing, and fish farming	1.4	1.3	1.9	2.5	2.6
Mining:	28.1	28.4	28.7	39.8	40.5
coal mining	6.1	5.5	7.7	8.1	8.8
crude oil and natural gas production	14.9	13.4	13.9	13.8	15.1
mining of metal ores	2.1	3.1	2.8	14.1	12.4
extraction of other mineral deposits	0.6	0.6	0.7	1.0	0.9
Provision of services in the field of mining	4.3	5.9	3.6	2.8	3.3
Manufacturing industries:	33.2	22.0	33.9	23.0	21.4
production of coke and petroleum products	3.9	3.7	4.2	3.9	3.9
production of chemicals and chemical products	2.3	2.1	2.1	2.6	2.6
Metallurgical production	21.5	10.5	21.4	8.8	8.1
Provision of electric energy, gas, and steam; air conditioning	20.3	15.9	17.4	17.1	17.8
Water supply; water disposal, waste collection and disposal, pollution elimination activities	2.8	3.5	4.0	4.3	4.4
transportation and storage	10.3	10.4	10.8	9.5	9.7
Total, thousand tons	17,477.5	17,068.1	17,295.1	16,951.5	17,207.7

* Since 2018—according to the Federal Service for Supervision of Natural Resources [114].

The official website of the Ministry of Natural Resources and Ecology of Kuzbass [116] provides data reflecting the level of the emissions of the pollutants into the atmosphere of the region, with an emphasis on the emissions from mining (Table 4). The main source of the emissions are mining enterprises (they account for approximately 68% of all emissions). The predominant pollutants from the mining are gaseous and liquid substances, among which sulfur dioxide (S_2O), carbon monoxide (CO), and nitrogen oxides (NO_2) are the leaders; for hydrocarbons, methane (CH_4) predominates. Over the past 5 years, the volume of emissions from mining enterprises has changed unevenly, in general; over the past 5 years, the number of emissions has increased by about 8%.

Table 4. Dynamics of emissions of major pollutants into the atmospheric air in Kuzbass, thousand tons (from 2017 to 2021) *.

Emissions	**Years**				
	2017	**2018**	**2019**	**2020**	**2021**
Total	1487.6	1383.1	1760.1	1611.8	1603.2
Mining:	920.8	839.7	1157.5	970.4	1085.2
Solid substances	146.8	138.4	154.9	139.9	140.8
Gaseous and liquid:	1340.8	1244.6	1605.2	1471.8	1462.4
S_2O	133.5	115.1	120.1	105.9	98.1
CO	274.7	250.9	284.1	274.1	275.8
NO_2	78.5	73.5	93.1	89.3	88.8
Hydrocarbons:	840.1	775.5	1032.9	967.4	979.8
Methane	839.8	774.2	1026.6	962.6	979.6

* according to the Territorial Body of the Federal State Statistics Service for the Kemerovo Region [117].

Figure 3. Disturbed territories of coal mines (photo from the KemSU collection).

The total area of the disturbed lands in Kuzbass is extremely high. According to the official statistics, about 100 thousand hectares have been violated in Kuzbass, and according to expert estimates, it is 1.5–2.0 times more. The area of technogenically disturbed lands is constantly growing—it is estimated that an average of 36 hectares of natural ecosystems are withdrawn for 1 million tons of coal mined. Thus, with an average annual production level of 250 million tons, about 9 thousand hectares are destroyed annually [121]. And only 30% of the territory of the region, where 5–10% of the population lives, meet satisfactory environmental conditions [116]. The total area of disturbed land in the area reaches 20 thousand hectares. A characteristic feature is the huge amount of production and consumption waste annually placed on these territories. A kind of "post-industrial desert" with unfavorable natural conditions was formed—the dustiness of the atmosphere, desiccation of the surface layers of air, and high temperatures in the summer.

Measures are also needed to improve the environmental situation in settlements located near coal enterprises. For example, methods of reclamation of technogenically disturbed lands.

5. Methods of Reducing the Impact of Coal Enterprises on the Environment

At all stages, from extraction to use in production, coal is a source of GHG emissions. There are two ways to solve the carbon footprint problem: by reducing the number of life processes that produce GHG emissions or by neutralizing these emissions. The attitude of the world community to the carbon footprint problem is ambiguous. On the one hand, they propose drastic measures—not to use coal at all and hydrocarbons in general and to switch to alternative energy sources (solar, wind, etc.) [122,123]. On the other hand, being one of the major sources of GHG emissions, the United States withdrew from the Paris Agreement in 2017, not considering it necessary to support it [124]. According to the EPA data [125], over the past 20 years in the US, methane emissions from the coal sector have decreased by a 40 Tg carbon dioxide equivalent (CO_2e). It is believed that this decrease is due to both a decrease in coal production and the transition from underground to open-pit mining [123]. The majority of both coal importers and exporters agree on the following: to reduce the negative impact of measures to restore the environment [124,126], because most of the carbon dioxide capture technologies in the technological process are quite expensive [127].

There are many different methods for reducing the anthropogenic impact (the impact of coal enterprises) on the environment [128–130]. Methods can be divided [131] by the application area (atmosphere; water bodies and aquatic bioresources) and impact objectives (the areas of production/consumption waste management; land reclamation and protection; and general methods and biodiversity conservation) [132]. Traditionally, [131,133] the methods for reducing the anthropogenic impact are divided into technological (loss prevention, the use of modern methods of production of blasting and mining operations, increasing the efficiency of subsoil development, design, the construction and commissioning of treatment facilities, the introduction of closed technological schemes with the use of water, reducing the negative impact on the environment, etc.), protective and preventive (the protection of substandard reserves in the subsurface, aquifers, objects on the surface, a reduction in the size of depression craters, the preservation of groundwater quality, the prevention of fires, etc.), environmental (environmental quality assurance and mining and biological reclamation), and organizational (the organization of the integrated use of subsurface and mineral resources, introduction of modern environmental management systems, annual professional development of employees in the field of ecology, etc.) [134,135].

Land resources are considered to be a significant object for restoration, measures related to land reclamation and restoration, and the preservation of biodiversity as close as possible to the state before extraction, in which reducing or disposing of the emissions of pollutants are important [136]. The reclamation of disturbed lands in the coal region is carried out in agricultural, forestry, and sanitary–hygienic directions [34,137].

In the work of Holl [138], criteria are formulated, the assessment of which is necessary for the choice of reclamation methods: the purpose of restoration (ecological and social); the surrounding landscape; ecosystem stability (the degree and speed with which the ecosystem restores its original structure and functions after a violation); and resources (the estimated cost of restoration). The methods for reclamation are divided into physical, chemical, and biological restoration [59]. It is noted that these methods work best in combination rather than independently.

The physical method (physico-mechanical) is aimed at reducing erosion, reducing soil compaction while improving its quality, and creating conditions for vegetation restoration. For example, this method is achieved by applying organic fertilizers (compost and limestone) to the soil, applying fertile soils brought from nearby sites. The chemical method is aimed at removing pollutants from the soil and restoring its pH [139]. Most often, chemical methods are closely related to physical ones. Thus, chemical methods include the introduction of chemical fertilizers (nitrogen, phosphorus, and potassium) and important micronutrients (zinc, copper, lime, etc.) into the soil [140]. The use of biocoal is a promising direction in physical and chemical methods. Biocoal is an additive obtained by pyrolysis (the raw materials are heated at a temperature from 300 to 800 °C in an environment with a low oxygen content) [141]. The addition of biocoal to the soil contributes to the carbon capture, increases the pH of the soil, and reduces the leaching of soluble macronutrients. In other words, biochar has the potential to increase carbon reserves in the soil, increase its fertility, and maintain the balance of soil ecosystems, opening up prospects for increasing yields [142].

The biological method (phytoremediation) suggests introducing microorganisms and/or green plants into the soil for phytoextraction and phytostabilization [143]. It is established that this method improves the quality of the soil and accelerates the restoration of vegetation. Bolan [144] describes phytoextraction (which includes the absorption and translocation of heavy metals by plants) and phytostabilization (plants and soil additives are used to immobilize heavy metals by the absorption and accumulation by roots, shoots, or deposition in the rhizosphere) as phytoremediation stages [145]. Masha [146] additionally distinguishes rhizofiltration and phyto-volatilization, noting the effectiveness of phytoextraction. Mirza [147] reviews the features of five phytoremediation technologies.

Grasses, shrubs, and trees can be used as plant objects of reclamation [148]. In Li [149], it is proposed to use native representatives of soils as a plant object of reclamation, because, firstly, they are more viable, and secondly, alien plant species can seriously change the local ecosystem. In [150], the ability of *Cannabis sativa* L. to grow and restore the soils of abandoned coal mines in Pennsylvania was studied. The results showed that these plants showed a high tolerance to heavy metals, which determines their prospects for use for the reclamation of disturbed lands.

However, there are serious concerns that having absorbed heavy metals, plants on disturbed lands can cause a toxic effect by entering the body of animals [151]. Bilski [152] conducted a study showing that barley (*Hordeum vulgare*), Sudan grass (*Sorghum bicolor*), rapeseed (*Brasica campestris*), rapeseed (*Brassica napus*), alfalfa (*Medicago sativa*), and perennial ryegrass (*Lolium perenne*) do not accumulate metals and are suitable for the reclamation of disturbed lands. These plants were grown on nutrient media with the addition of coal ash. It was found that barley and Sudan grass did not accumulate toxic amounts of heavy metals even when grown on media containing 100% coal ash.

6. Russian Experience in Reclamation of Disturbed Lands

The first attempts to neutralize the consequences of the negative impact of mining, including coal, on the environment by purposefully forming vegetation cover on disturbed lands began to be undertaken in the industrialized countries of Europe at the beginning of the twentieth century. On the territory of the former USSR, this process began in the 1950s of the twentieth century in the Donbass [153]. It should be noted that foreign work on the reclamation of man-made landscapes through the formation of vegetation pursued agricultural and forestry purposes, but at the end of the twentieth century, more attention was paid to the environmental component. Not only European researchers are turning to the Kyoto Protocol. For example, "Climate Change Policy in Japan: From the 1980s to 2015" by Yasuko Kameyama was published in 2016. The author notes that Japan is vulnerable to global environmental threats. Therefore, the State takes a responsible approach to the development of a climate change policy. The scientist considers environmental, economic, and political factors that determine the formation of the agenda, including the ratification of the Kyoto Protocol [154].

Coal mine methane is closely related to coal mining. After the end of the coal mining and conservation, the mine continues to emit methane for a long period. Authors [23] claim that by 2100, methane emissions from operating underground mines will increase by 4 times, while emissions from abandoned mines will increase by 8 times. For this reason, not using coal and not mining it will not lead to the desired reduction in the concentration of greenhouse gases in the atmosphere. The methods for their safe absorption and neutralization are needed. The biological methods for reducing the carbon footprint are the most attractive.

Among the environmental components to reduce the negative impact of the carbon footprint are the following. In recent years, for the reclamation of disturbed lands, there has been a transition from the simple sowing of disturbed areas with grasses and the planting of woody plants to a more meaningful and integrated approach, which consists of the development of individual reclamation projects taking into account many factors, including the climate, relief, fertility level, physical properties of rocks, etc. [155]. To restore disturbed lands, various reclamation technologies are used, taking into account the specifics of the local natural resources and the physical and agrochemical properties of the substrates; special attention is paid to the selection of suitable plant species for the formation of vegetation cover. Nevertheless, the main condition for the successful development of technogenic landscapes is the creation of favorable edaphic factors for the formation of a primary vegetation cover. A large number of works on various types of disturbed territories located in various climatic conditions are devoted to these issues. Nevertheless, the studies on the restoration of vegetation cover in reclaimed areas with carbon enrichment waste continue to be relevant [156].

Currently, the so-called carbon polygons (carbon farms) are a promising direction. In February 2021, the President of the Russian Federation adopted a decree "On measures to implement the state scientific and technical policy in the field of environmental development of the Russian Federation and climate change", for the implementation of which, within the framework of the carbon dioxide emission reduction program in Russia, it is planned to create carbon landfills sites (in the first stream of the project, there are seven pilot geostrategic regions, including Kaliningrad, Sakhalin, Novosibirsk, Tyumen, Sverdlovsk regions, as well as the Chechen Republic and Krasnodar Krai), where the conditions for the absorption of CO_2 are being worked out [157]. Plants bind carbon dioxide to use it for photosynthesis. The more plants there are, the more carbon dioxide is removed from the atmosphere, which affects the concentration of greenhouse gases [157]. At such sites, it is recommended to use coal dumps on which plant objects are planted for land reclamation. On the one hand, the lands are being restored; on the other hand, the concentration of carbon dioxide is decreasing.

The study of Sheremetov [158] presents a list consisting of 20 species and 4 genera of macrophyte plants, the use of which is relevant for phytoremediation, in the coal region of Russia–Kuzbass, in particular. The presented plants are widely distributed on the territory of the Kemerovo region–Kuzbass. So, *Iris pseudacorus* L. is capable of purifying objects from nitrogen and phosphate compounds, heavy metals; *Acorus calamus* L. and species of the genus *Sparganium* are able to accumulate sulfur; *Nuphar lutea* (L.) Smith—cobalt; *Potamogeton pectinatus* L.—radionucleides; *Lemna minor* L. is noted as a species accumulating copper, boron, lead, cadmium, iron, and mercury; and *Ceratophyllum demersum* L.—zinc, copper, cadmium, lead, etc. But the data presented in the review require practical verification.

Currently, reforestation is the leading direction for the restoration of lands disturbed by the coal industry in Kuzbass (Western Siberia, Russia). This direction is the most economical and easiest to implement, and forest communities best transform disturbed lands into productive habitats. The impact on the ecosystem through reforestation and the creation of plant communities on landfills is an important criterion for the restoration of technogenically disturbed lands [159]. Modern recommendations on the forest reclamation direction are focused on the creation of monocultures that are insufficiently stable, do not create a nature-like structure of plant communities, and are not stable for a long period of time [160].

The main forest-forming species on coal dumps are *Betula pendula*, *Pinus sylvestris*, and *Populus tremula*. The related species are *Acer negundo*, *Crataegus sanguinea*, *Hippophaë rhamnoides*, *Lonicera tatarica*, *Malus baccata*, *Padus avium*, *Rosa acicularis*, *Salix cinerea*, *Sambucus sibirica*, *Swidina alba*, and *Ulmus pumila*. A more successful reforestation is achieved under favorable environmental conditions (lowlands, northern slopes with a steepness of less than 15°, or flat areas with a well-defined microrelief). The renewal of birch as a whole can be considered satisfactory on almost all the dumps of the southern forest-steppe of the Kemerovo region. The abundance of renewal of the invasive species Acer negundo is maintained due to the constant introduction of seeds into landfills (most seedlings and young undergrowth of the plant die before reaching the generative age) [159,161,162].

Today, stable self-sustaining tree–grass communities with a high biological diversity and maximum compliance of the conditions of man-made habitats with the ecological and biological features of forest vegetation in the foreground are being formed. The use of a wide range of trees and shrubs from the composition of belt vegetation is an important condition for the formation of forest plantations. As a shrub layer, in addition to coniferous and deciduous crops, it is advisable to use shade-tolerant species (rowan—*Sorbus sibirica*, elder—*Sambucus sibirica*, and acacia—*Caragana arborescens*) and other types of shrubs that form the undergrowth of local tree species. In young plants, it is recommended to plant perennial grasses (cereals, legumes, and compound flowers) to activate the soil-forming process. In all cases, it is necessary to provide fire-extinguishing measures [163].

Lamanov's study [164] considers the possibility of growing rare and endangered plants of Siberia (*Allium altaicum*, *Alfredia cernua*, *Stemmacantha carthamoides*, *S. carthamoides subsp. chamarensis*, *Campanula trachelium*, *Sedum pallescens*, *Glycyrrhiza uralensis*, *Iris pseudacorus*, *Hemerocallis minor*, *Paeonia anomala*, *Festuca gigantea*, and *Rheum altaicum*) for reclamation in disturbed areas. It was found that it is optimal to grow *Festuca gigantea*, *Campanula trachelium*, *Paeonia anomala*, and *Glycyrrhiza uralensis* on dumps without applying a fertile soil layer. When applied to the dumps of a fertile soil layer—*Alfredia cernua*, *Iris pseudacorus*, *Rheum altaicum*, and *Hemerocallis minor*. *Stemmacantha carthamoides* grows in all the conditions considered. Pine (*Pinus sylvestris*) is actively used for the reclamation of dumps in Kuzbass [165]. In the study of Tsandekova [166], the stability of *Pinus sylvestris* grown in various ecological conditions of disturbed coal mine lands was evaluated by the activity of peroxidase in needles and the vital state of plantings. The planting of pine trees of age I (10–15 years) and II (20–25 years) were selected as the objects of research. The conducted studies have established that on a planned dump without the application of fertile soils, ordinary pine of the first and second age categories with minimal values of peroxidase activity has the highest score of the vital condition. Obviously, this is due to the fact that pine belongs to oligotrophic plants that are not very demanding to soil conditions. The highly developed pine root system is able to extract the necessary amount of nutrients from poor soils in extreme environmental conditions. The studied indicators can be used in forest reclamation to determine the mechanisms of the stability of woody plants in conditions of disturbed lands of coal mines. Ufimtsev [167] described that the common pine *Pinus sylvestris* L., common sea buckthorn *Hippophae rhamnoides* L., and weeping birch *Betula pendula* Tristis are suitable for use at the regional level for reclamation. For effective land reclamation, in addition to the formation of a plant community (flora), it is necessary to maintain the ecosystem as a whole, i.e., the formation of microbiota and fauna in the territories [168,169]. It is important to use a combination of land reclamation methods to achieve a maximum result to improve the ecological situation of the region [170].

The use of dumps exclusively in the forestry direction significantly narrows their use as objects for the creation of recreational areas and sports facilities and for water management. Moreover, the creation of carbon farms based on specially selected greenery at such polygons could become a high-tech business in demand. The high potential of the Russian Federation for carbon deposition by biological systems will support the development of a network of Russian carbon polygons. There is already a precedent for the creation of a generally accepted methodology for assessing carbon deposition (carbon polygons in Italy) [171,172]; Russian soil scientists and geographers took a central part in its preparation [173]. At a new level, the importance of soil organic substances for soil health, its fertility, maintaining the species diversity of soil organisms, and providing other ecosystem services related to soil is being realized [174]. In natural ecosystems, the circulation and storage of organic carbon are regulated by a variety of factors [175] that are subject to human influence and global climate change [176]. However, it has been established that the creation of carbon polygons is quite an expensive undertaking. The maintenance of 1 hectare of a carbon wood farm ranges from 260 to 305 thousand RUB (up to 5000 in USD equivalent). To equalize such costs, it is necessary to develop an effective methodology for accounting for the absorption of greenhouse gases from the atmosphere by green spaces, which will influence the global quota market and minimize the cross-border carbon tax introduced by the European Union in 2022–2023 [177].

7. Conclusions

The complete abandonment of fossil fuels, including hydrocarbons, as an energy source is unlikely in the coming decades. Despite decades of solving the carbon footprint problem, there is still no universal approach. Recommendations for enterprises, including coal mining ones, have been formulated. But no methods of total prohibition are effective. The solution is in harmony, in achieving a balance between the emission and deposition of greenhouse gases. In this case, biological recovery methods are the best alternative. The technique of carbon polygons/farms has definite prospects, but the development of its technologies requires complete studies of all stages of biological reclamation.

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