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The raw materials industry in the face of environmental challenges: trends and mitigation strategies

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Abstract: The paper concerns selected environmental issues associated with the global raw materials sector, focusing on ores, coal, cement, and quarrying. Global mining production of mineral resources exhibits a steady upward trend, currently reaching about 19 billion tonnes per year, with energy resources holding a dominant share in both worldwide production and the economic structure of the sector. Such an immense scale of operations generates severe environmental problems, such as contamination of ecosystems and landscape transformation. The aggregate production sector is primarily responsible for air pollution through particulate matter emissions, as well as exhaust gas emissions from transportation. In the coal industry, key challenges include fugitive methane emissions during extraction and massive amounts of carbon dioxide generated during combustion. Cement plants, in turn, represent a major source of nitrogen oxides, sulphur dioxide, and toxic heavy metals such as mercury, lead, and chromium, as well as CO_2 (clinker production). The primary objective of this paper is to highlight these issues in detail and to present modern technical methods for their effective mitigation. The implementation of integrated ecological management strategies enables the raw materials industry to successfully reduce emissions while maintaining cost efficiency.

Keywords: mineral processing, environment, raw materials, dust, LCOE

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1. Global production and value of raw materials

The mining production of raw materials has reached approximately 19 billion tonnes (Reichl & Schatz, 2025), with a steady increase observed over the last four decades. The following types of raw materials are included in this list: mineral fuels (coal, oil, gas, uranium), iron and ferroalloys, non-ferrous metals, precious metals, and industrial minerals. The energy raw materials constitute the highest share in the total global production of raw materials, with a global yearly production exceeding 16 billion metric tonnes (Fig. 1). It is also worth noting that this summary does not include aggregates, the production of which is estimated between 20 and up to even 40 billion metric tonnes. More precise estimation of global aggregate production is difficult due to the very high number of rather small deposits, low production capacity of individual plants, easy access to these deposits, and huge dispersion of resources around the world. The list does not include the rare earth elements (REE), which equals approximately 300,000 tonnes.

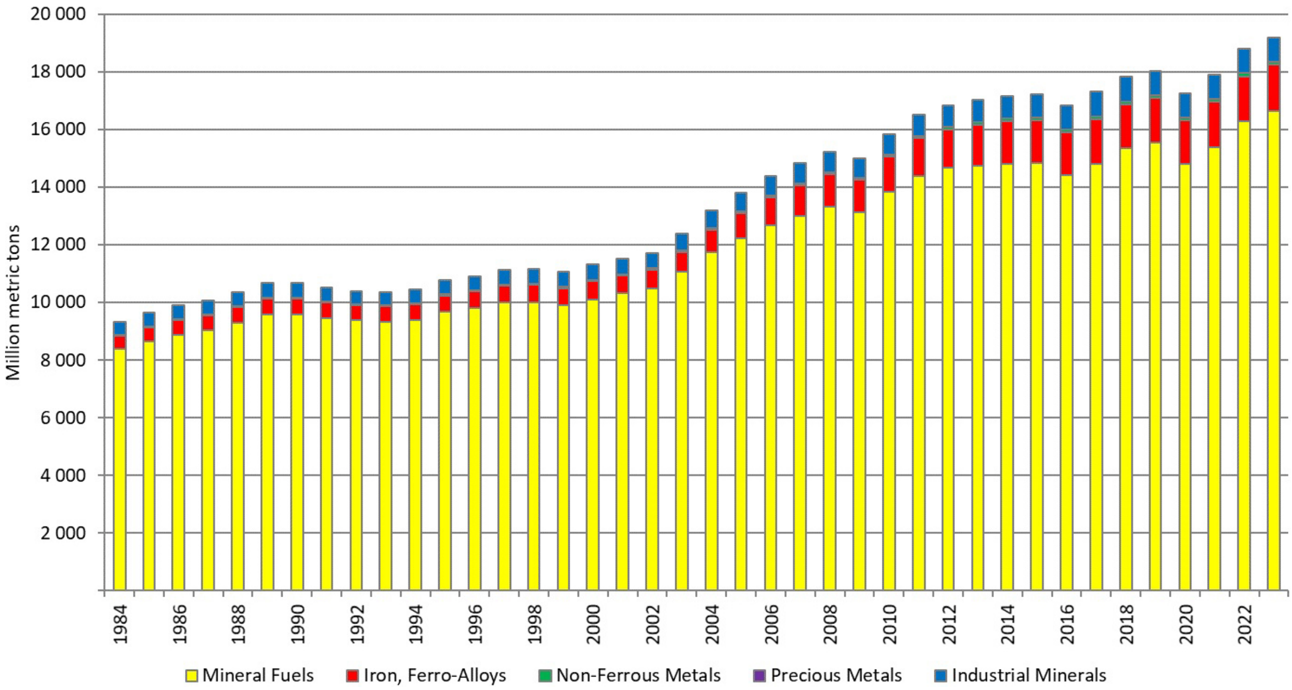

Fig. 1. Global mining production of individual types of raw materials (Reichl & Schatz, 2025)

The volume of mining production of raw materials is diverse across the continents. Figure 2 presents the data showing the share of individual regions in this production. These results indicate the increasing role of Australia and Asia, a steady position of Africa and both Americas, and a decreasing impact of Europe. Australia becomes the leader in 2024 with around a 500% increase compared to 1984. In contrast, Europe's share has decreased by 50% over the last four decades.

The value of mining production within individual groups is also diverse. All mined energy raw materials have the highest value, which constitutes an even higher share in monetary units (over 99%) than in metric tonnes (approximately 85%). However, if the volume of total global aggregate production is included, the share of energy resources mass decreases to one third. This serves to highlight the strategic position of all fuel minerals. Specific data are presented in Tab. 1.

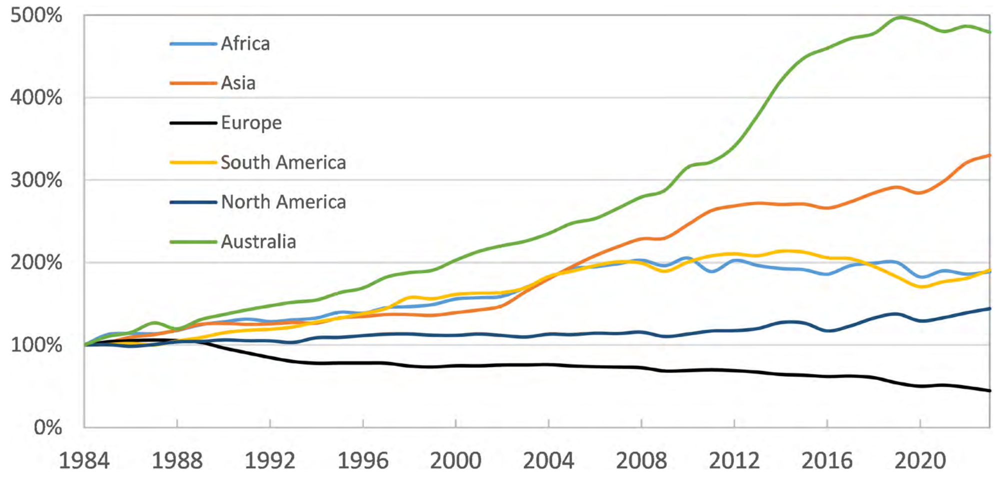

Fig. 2. Trends in raw materials production for specific regions (Reichl & Schatz, 2025)

Tab. 1. Estimated annual value of global production of selected mineral and energy commodities based on average market prices in 2026

Type of raw material	Average unit price [USD/kg]	Value of global production [USD · 10^{12}]
Crude oil	0.5	2,300
Coal	0.15	1,400
Aggregate	0.02	800
Gold	165,000	570
Copper	12.6	290
REE	300	90
Silver	2,550	80
Platinum	64,000	13

Analysing the results presented in Tab. 1, it can be seen that although gold has by far the highest unit value, crude oil, coal, and aggregates generate the greatest total annual production value due to their enormous production volumes. Together, these bulk commodities account for approximately USD 4.5 trillion of annual global production, underscoring their economic importance and the significance of mitigating their environmental impacts.

The raw materials industry is characterised by high mining production volumes and relatively high value, followed closely by a huge environmental nuisance. It is associated with intense landscape transformation (sometimes devastation) resulting from raw materials extraction and disturbances for inhabitants living in the area surrounding the mining exploration. The most immediate effects are dust and noise pollution, but other emissions (like gases, chemical residues) and soil or water contamination should also be underlined. The main purpose of this paper is to highlight selected environmental aspects related to raw materials sectors and present methods for mitigating them.

2. Primary types of emissions in major raw materials sectors

The raw materials sector comprises various types of industries, each of which operates differently, with differing overall effectiveness and environmental impact. These industries can be classified from different points of view, depending on which issue is being analysed. The characteristics have been formulated from the scope of individual types of resources processed and the final products obtained, while indicating the major environmental impacts of these sectors.

2.1. Aggregates

Aggregates are among the raw materials produced in the highest volumes worldwide and constitute the fundamental basis for infrastructure development, construction, and transportation systems. Compared with other mineral resources, the quantity of rock material extracted and processed is exceptionally high, while the unit price of the final product remains relatively low. However, industries involved in rock material extraction and aggregate production are major contributors to air pollution, primarily through dust and particulate matter emissions. Operational practice indicates that dust pollutants of various types are generated during quarrying, mining, and mineral processing operations, which consist of coarse and fine crushing operations and a series of screenings in the case of aggregate production. Depending on the measurement methodology, particulate pollution can be described as suspended particulate matter (SPM) in general or classified into specific fractions such as PM_{10}, $PM_{2.5}$, and PM_1. In addition to dust emissions, aggregate production processes may also generate gaseous pollutants such as CO_2, SO_2, and NO_x, which may exceed permissible environmental limits under certain operational conditions. These emissions originate mainly from fuel combustion in heavy mining equipment and transport vehicles and can contribute to broader environmental problems such as acid rain and smog. Noise pollution may also constitute a significant nuisance, particularly in areas located close to mining and processing plants (Bascetin et al., 2011; McKenna Neuman et al., 2024; Nagaraja et al., 2025; Lee et al., 2021; Saramak & Naziemiec, 2019; Saramak et al., 2022).

2.2. Coal

The coal sector is characterised by one of the highest production volumes worldwide and remains an important component of the global energy system. Numerous studies have demonstrated that the coal mining and processing industry, as well as coal combustion during its commercial utilisation, contribute significantly to environmental pollution and climate change. One of the most immediate and visible forms of pollution, particularly during the mechanical processing and transportation of coal, is dust emissions. Fine particulate matter ($PM_{2.5}$ and PM_{10}) is especially hazardous because it can penetrate deep into the respiratory system and contribute to respiratory and cardiovascular diseases (Brook et al., 2010). In addition to its effects on human health, coal dust deposition may negatively affect soil quality, vegetation, and nearby water systems (Bhanot et al., 2025; Du, 2018). Gaseous emissions also represent a major environmental concern, especially during underground coal extraction.

Methane (CH_4) is considered one of the most significant greenhouse gases due to its high global warming potential. Scientific studies indicate that fugitive methane emissions from coal mines contribute to climate change and represent a major challenge for emission reduction policies (Aslamiya et al., 2023). It should also be emphasised that nearly 80% of total emissions associated with coal are related to carbon dioxide (CO_2) generated during combustion. Coal-fired power plants release large quantities of CO_2, sulphur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter into the atmosphere. These pollutants contribute to global warming, acid rain formation, photochemical smog, and the long-term deterioration of air quality (Nelson, 2023; Masto et al., 2021; Pudasainee & Gupta, 2015). Coal combustion also produces hazardous by-products such as fly ash and bottom ash, which can create further environmental challenges. Various studies (Babbitt & Lindner, 2005; Huang et al., 2024; Liu & Liu, 2020; Saramak et al., 2022) highlight the problem of environmental emissions and emphasise the need for stricter environmental regulations and cleaner technologies in the coal sector.

2.3. Cement

The cement industry also contributes to air quality deterioration at both the local and regional scales. Cement manufacturing processes generate nitrogen oxides (NO_x), sulphur dioxide (SO_2), particulate matter (PM), volatile organic compounds (VOCs), and trace heavy metals released during combustion processes, not to mention a significant amount of CO_2 emissions. Nitrogen oxides and sulphur dioxide contribute to the formation of acid rain, photochemical smog, and secondary particulate matter, which can adversely affect ecosystems, climate processes, and human health. In addition, high-temperature kiln operations promote the formation of NO_x through thermal oxidation mechanisms, making cement plants an important anthropogenic source of reactive nitrogen compounds in the atmosphere (Ibrahim et al., 2012; Karstensen et al., 2016; Verma et al., 2023).

Another environmental concern associated with the cement industry is the emission of toxic heavy metals such as arsenic, cadmium, mercury, lead, and chromium. These contaminants may originate from natural raw materials, alternative fuels, or waste-derived feedstocks commonly used in modern cement production. Scientific investigations have demonstrated that prolonged exposure to heavy metals can result in severe toxicological effects on human health and the environment (Bărbulescu & Hosen, 2025). Once emitted into the atmosphere, these metals can be transported over considerable distances and subsequently deposited in soils and water bodies, where they may enter the food chain and pose long-term ecological and public health risks.

Particulate matter emissions from cement plants are also recognised as a significant environmental concern, especially in areas located near cement manufacturing facilities. Recent environmental studies have highlighted the cumulative effects of combined pollutant exposure, suggesting that interactions among particulate matter, sulphur compounds, and heavy metals may intensify toxicological impacts beyond those caused by individual pollutants alone. Consequently, the environmental impact of cement manufacturing extends beyond direct emissions and includes broader implications for environmental sustainability and public health protection. The study by Karstensen et al. (2016) emphasised the urgent need for stringent emission control strategies and continuous environmental monitoring in cement manufacturing facilities. The author also stressed the importance of regular emissions assessments and the integration of sustainable production practices aimed at minimising the environmental footprint of the cement sector.

2.4. Ore processing

Ore processing plants generate virtually all major types of atmospheric pollutants; however, the most significant contributors to environmental emissions are greenhouse gases (GHGs), particulate matter, and toxic pollutants. Carbon dioxide (CO_2) emissions in ore processing are primarily associated with energy-intensive operations within the technological circuit, such as crushing, grinding, screening, and beneficiation processes (Aydogdu & Duzgun, 2025). Dust generation constitutes a significant environmental problem in ore processing plants, and the concentration of particulate pollutants may exceed 5,000 mg/m^3. Intensive dust generation can be observed particularly during material crushing, especially in crushers with open or semi-open crushing chambers, such as jaw, gyratory, and hammer crushers (Saramak & Naziemiec, 2019; Susanto et al., 2024). Sulphur oxide (SO_x) and nitrogen oxide (NO_x) emissions are observed especially in iron ore pelletising plants. These pollutants are generated primarily during the induration process, in which iron ore pellets are hardened at high temperatures. The combustion of fuels and the oxidation of nitrogen-containing compounds present in the raw materials contribute to the release of these emissions (Bolen, 2014; Trang et al., 2006). It should be emphasised that global iron ore production reached approximately 1.6 billion tonnes in 2024, accounting for more than 93% of total ore production, making the environmental impact of this sector substantial.

It should also be noted that emissions of dioxins and furans occur during ore sintering processes, the production of secondary aluminium and primary zinc, and copper smelting operations (Grochowalski et al., 2007; Rezaei et al., 2013). Processing residues often contain hazardous metals such as lead (Pb), cadmium (Cd), and zinc (Zn), which may leach into the environment under acidic conditions (Sethurajan et al., 2016). Processes of chemical separation, leaching, flotation, and other methods of chemical and physical separation are a source of various chemical pollutants, organic wastes, and other dangerous contaminants. The contamination of process waters used in wet operations is a separate issue, but this topic is out of the scope of this paper. Finally, the global transportation of ores for processing further contributes to the overall carbon footprint of the mining and metallurgical sectors.

3. Average costs of energy production

The mining and mineral processing industry is highly energy intensive; therefore, particular attention should be paid to the efficient utilisation of energy. The average costs of electricity generation per MWh can be estimated as follows (Stańczuk, 2025; Świerszcz et al., 2025):

- conventional energy sources:
  - gas-fired power plants (CCGT): 110–120 USD/MWh;
  - coal-fired power plants (hard coal and lignite): 170–210 USD/MWh;
- non-conventional energy sources:
  - photovoltaics (PV): 50–90 USD/MWh (depending on the size of the installation);
  - onshore wind power: 70–90 USD/MWh;
  - offshore wind power: 80–110 USD/MWh;
  - hydropower plants: 50–70 USD/MWh.

It should be noted that, with conventional energy sources, namely gas-fired and coal-fired power plants, the unit cost of electricity generation is highly dependent on fuel prices, which are characterised by considerable volatility. This is particularly evident in the case of natural gas. On top of this, electricity generation from fossil fuels is subject to emission allowance costs, which have increased over the last decade from approximately 6–7 USD per tonne of CO_2 emitted into the atmosphere to more than 85 USD per tonne today. Emission charges constitute a significant component of electricity generation costs in coal-fired power plants, as the production of 1 MWh of electricity results in average emissions of approximately 1 tonne of CO_2. For gas-fired power plants, CO_2 emissions may be 2.5–3.0 times lower, depending on the technology employed. Although emission charges result from regulatory mechanisms rather than technological factors, they substantially influence the overall economics of conventional electricity generation.

The unit costs of electricity generation from non-conventional energy sources are generally lower than those associated with conventional technologies (Aldersey-Williams & Rubert, 2019). However, the primary challenge related to renewable energy sources is the stability and continuity of the energy supply. The effective operating time of photovoltaic systems is approximately 15 h per day during favourable summer periods and around 8 h per day during winter, corresponding to periods of effective solar irradiation. The effective operating time of wind power plants is more difficult to estimate due to uncertainties in wind speed and wind resource forecasting. Based on long-term meteorological observations, the average effective operating time can be approximated at approximately 30% of a day, corresponding to about 7 h of full-load operation (Twidell, 2021). Therefore, the levellised cost of energy (LCOE) indicator is widely used to compare the efficiency and economic viability of different electricity generation technologies (Lazard, 2025). The LCOE is one of the most commonly applied economic indicators in the energy sector and is used to estimate the average cost of generating a unit of energy over the entire operational lifetime of an installation (Aldersey-Williams & Rubert, 2019).

$$LCOE = \frac{Total\ Discounted\ Lifetime\ Costs}{Total\ Discounted\ Energy\ Generated}$$

The LCOE indicator is calculated as the ratio of all discounted costs incurred during the lifetime of a project to the total discounted electricity generation. The calculation typically includes capital expenditures, operation and maintenance costs, fuel costs (where applicable), and decommissioning costs incurred at the end of the facility's operational life. The use of the LCOE indicator is essential because investment costs alone do not provide a complete picture of a project's economic viability. Some technologies are characterised by high initial capital expenditures but very low operating costs, whereas others require lower initial investments but generate substantial operating expenses. The LCOE incorporates all of these factors into a single metric, thereby facilitating economic analyses and investment decision-making. One of the key advantages of the LCOE is its ability to compare different energy technologies using a uniform methodology. The indicator takes into account the entire lifecycle of an installation, providing more comprehensive information than analyses based solely on investment costs. Finally, it makes it possible to assess the impact of changes in economic parameters, such as construction costs, operating expenses, and financing conditions.

The average electricity generation costs for selected technologies, determined using the LCOE methodology, are as follows:

- gas-fired power plants: 139 USD/MWh;
- coal-fired power plants: 122 USD/MWh;
- photovoltaics: 51 USD/MWh;
- wind power: 61 USD/MWh;
- geothermal energy: 86 USD/MWh;
- nuclear energy: 180 USD/MWh.

It can be observed that technologies based on renewable energy sources are generally more economically attractive than electricity generation technologies based on fossil fuels. However, renewable energy technologies are limited by significant variability and intermittency of supply, which is of particular importance for industrial energy consumers. One possible solution is the implementation of hybrid energy supply systems in industry. Such systems combine multiple generation sources – typically conventional and renewable energy technologies – with supporting solutions such as energy storage systems into a single integrated power supply network for industrial facilities. This approach can reduce average energy costs, improve voltage stability, and enhance resilience against interruptions in the electricity supply.

4. Technological challenges and mitigation strategies

The negative environmental impact of the quarrying (aggregate production), mining, and mineral processing industry is a complex and multifaceted issue. The main approaches to mitigating these impacts include pollution monitoring and pollution control. Monitoring activities provide detailed information on the types, intensity, and dispersion of pollutants within individual components of the environment. Pollution control measures may focus either on reducing pollutant generation at the source (for example, during crushing operations) or on limiting pollutant dispersion. In the case of specific technological operations, environmental performance can be improved through the implementation of more efficient technologies. For example, replacing conventional jaw crushers with high-pressure grinding rolls (HPGRs) can significantly reduce unit energy consumption. Lower energy consumption translates into a reduced demand for electricity generation and, consequently, lower emissions associated with energy production (Norgate & Haque, 2010). Another approach involves the use of renewable electricity and cleaner fuels, which can substantially reduce greenhouse gas (GHG) emissions (Lu et al., 2023). Although renewable energy systems often require higher initial capital expenditures, their long-term operation may provide both environmental and economic benefits. Pollution control also includes the application of technologies such as activated carbon filtration systems and baghouse filters, which effectively reduce toxic atmospheric emissions (Bolen, 2014).

Considering the above, the following mitigation strategies can be distinguished:

- Development of mining and mineral processing technologies. Technological progress and the implementation of innovative solutions, processes, and equipment within mineral processing systems improve the recovery efficiency of valuable minerals. This simultaneously enhances economic performance and reduces raw material losses. Examples include advanced mineral separation technologies, such as chemical and biological in situ beneficiation methods, as well as more energy-efficient comminution operations. In the coal sector, modern combustion technologies are applied during energy generation, making coal utilisation more efficient and less environmentally burdensome. Intensive research is also being conducted on coal gasification and hydrogenation technologies aimed at reducing environmental impacts and improving resource utilisation.
- Application of filters and protective barriers to reduce emissions. The use of filtration systems and protective barriers during mining and mineral processing operations can significantly reduce the emissions of dust and other

atmospheric pollutants, particularly in surface mining operations. Dust collection systems, dust screens, and water spraying systems are commonly employed to suppress the suspension of fine particles generated during extraction, transportation, and crushing processes. Protective barriers, such as earth embankments and acoustic screens, further limit the spread of dust and noise into surrounding areas. For example, installing baghouse filters in mineral processing plants can remove more than 99% of particulate matter from exhaust air. More advanced technologies such as high-pressure dust control fog systems generate extremely fine water droplets that bind airborne dust particles. These systems are typically installed in close proximity to dust sources, such as crushers and conveyor transfer points, effectively reducing dust emissions while consuming significantly less water than conventional spraying systems. They can also be automatically controlled using data obtained from sensors monitoring airborne dust concentrations.

- Utilisation of renewable energy sources and closed-loop production systems. The adoption of renewable energy sources and closed-loop production systems contributes to reducing material losses and improving production efficiency while supporting sustainable development within the mining and mineral processing industry. The use of electricity generated from photovoltaic installations or wind turbines reduces dependence on conventional energy sources and lowers greenhouse gas emissions. In closed-loop production systems, water and production by-products are recovered and reused, reducing both raw material consumption and the quantity of waste discharged into the environment. Production losses can also be minimised through advanced monitoring and process automation systems that improve resource utilisation efficiency. One example of such technology is AI-based digital production management systems, which continuously analyse process parameters and optimise the consumption of energy, water, and materials.
- Land reclamation and revitalisation. The reclamation of post-mining areas involves restoring ecological, functional, and landscape values to land degraded by mining activities. This process includes reshaping terrain, restoring topsoil layers, and establishing appropriate vegetation cover, which helps reduce erosion and restore local ecosystems. Such measures mitigate the environmental impacts of resource extraction while improving the visual and ecological quality of the landscape. Examples of modern reclamation technologies include hydroseeding, which involves spraying a mixture of seeds, fertilisers, and binding agents onto degraded surfaces to accelerate vegetation growth and soil stabilisation. Another example is phytoremediation, which utilises specially selected plant species to remove heavy metals and other contaminants resulting from mining activities. These plants either absorb harmful substances from the soil or immobilise them, thereby limiting their migration within the environment. Phytoremediation is a relatively inexpensive and environmentally friendly technique that simultaneously supports the gradual restoration of vegetation cover on degraded land. Monitoring of reclamation progress increasingly relies on unmanned aerial vehicles (UAVs) and LiDAR scanning technologies, which are also used for the precise planning of land restoration following mine closure. The revitalisation of post-mining areas involves assigning new social, economic, or recreational functions to degraded sites after mining operations have ceased. This process encompasses not only environmental improvement but also the redevelopment of land in ways that provide benefits to local communities. Former excavations and industrial facilities may be transformed into

parks, reservoirs, cultural centres, sports facilities, or investment zones. Revitalisation contributes to improving residents' quality of life and enhancing regional attractiveness. One example of a modern solution is the application of Geographic Information System (GIS) technology for planning and managing revitalisation projects. GIS enables detailed spatial analyses and supports the optimal redevelopment of post-industrial and post-mining areas.

5. Summary and conclusions

The article presents selected environmental aspects of the quarrying and mineral processing industry, as well as the conditions and methods for mitigating its negative impacts on the natural environment and human health. In this context, particular attention should be paid to the following issues:

- clean technologies and energy efficiency, which contribute to optimising natural resource and fuel consumption, thereby reducing greenhouse gas emissions and lowering production costs;
- sustainable resource and waste management, with a focus on minimising both the quantity and toxicity of generated waste while reducing resource losses and improving material efficiency;
- pollution control and environmental quality improvement in the vicinity of industrial facilities, thereby minimising health risks for employees and local communities;
- integrated environmental and resource management, achieved through the implementation of circular economy principles and comprehensive environmental monitoring systems;
- societal impacts, emphasising the need for a holistic approach to addressing environmental and public health challenges and ensuring that environmental protection and human health considerations are fully integrated into public policy and industrial development strategies.

Implementing these measures is essential for achieving sustainable development in the mining and mineral processing sector. A balanced approach that combines technological innovation, environmental protection, economic efficiency, and social responsibility can significantly reduce the environmental footprint of mineral processing activities while supporting long-term industrial competitiveness and societal well-being.

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