

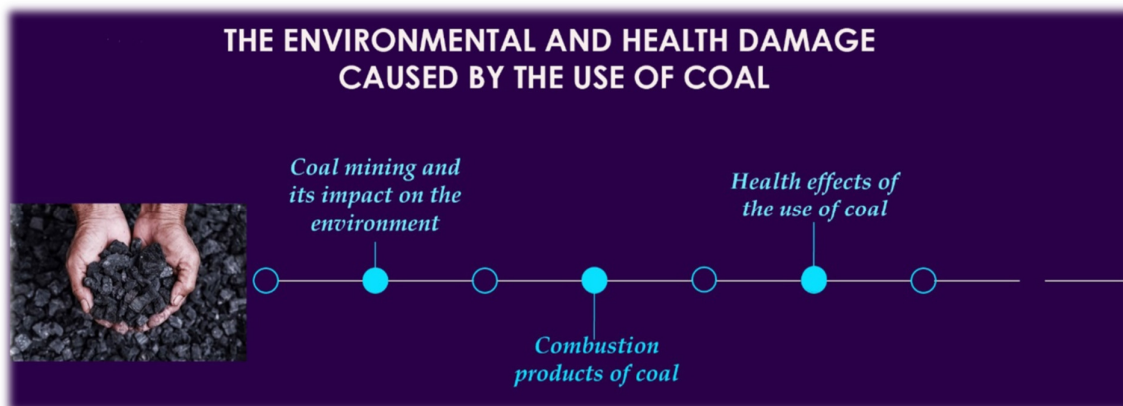
The environmental and health damage caused by the use of coal

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Abstract

Alongside to oil and natural gas, coal is the most abundant non-renewable fossil fuel resource currently utilized in the world. Although continuous efforts have been made in recent decades and in the present to replace the use of coal with various alternative energy sources (hydro, nuclear, wind, solar), coal is expected to remain the most important source of heat and electricity in the world for the foreseeable future. Despite the undeniable importance of coal to the world, its use causes serious damage to the environment and human health. In this lecture text, the destructive effects of coal mining and its utilization on the environment (pollution of air, soil and water, loss of forests, destruction of habitats, noise pollution, dust, vibrations, chemical leaks, erosion, sedimentation, abandonment of the coal mining site) will be discussed in detail. Particular attention is paid to the health effects of coal use (respiratory effects, cardiovascular damage, cancer and other chronic diseases, reproductive health, neurological degeneration, mental health and social damage, radiation sickness, etc.).

Graphical abstract



Keywords Coal · Damage · Environment · Human health

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Introduction

Coal is a black or brownish-black sedimentary rock formed over millions of years through the process of the decay and transformation of plant material into peat which is later converted into coal under the pressure and heat of deep burial (Mancuso and Seavoy, 1981; McGhee, 2018; Cleal and Thomas, 2005; Sahney, et al., 2010, Jovanovski et al., 2023). Its chemistry and geology have been the subject of interest of many researches (Warwick, 2003; Orem and Finkelman, 2003; Speight, 2013; Thomas, 2020; Demirbas, 2007; Jovanovski et al., 2023). Along with petroleum and natural gas, coal is the most abundant fossil fuel resource currently utilized worldwide and is expected to remain the most important source of heat and electricity in the world for the near future (Warwick, 2003; Whitaker, 1959; Životić et al., 2024).

In general, mining is a major economic factor, with far-reaching impact on the environment, labour and society, both locally and globally. It provides essential materials for consumer goods and supports the activities of almost all other sectors, including agriculture, manufacturing, transportation, utilities, communications, and construction. In many developing countries, mining is a major contributor to gross domestic product (GDP) and often accounts for the lion's share of foreign exchange earnings and foreign investment (Remoundou and Koundouri, 2009). However, the mining sector faces major challenges. The working environment in coal mines can be unique and hazardous. Challenges include mining near urban areas and critical structures, deeper excavations with highwalls under increased geological stress and hydrostatic pressure. The sector's environmental footprint is substantial and enduring, and is often exacerbated by poor management and restoration practices of mined landscapes. Environmental concerns are becoming increasingly pressing for the industry and its workers.

As we already know, energy is harnessed from natural resources such as sunlight, wind, water, and fossil fuels. These resources are categorized into renewable (abundant and easily restored), and non-renewable (with limited supply). Both types can serve as primary energy sources and can be converted into secondary forms of energy.

Electricity is a crucial resource whose demand increases every year. It is a secondary form of energy that is obtained from various primary sources. Primary energy comes directly from natural sources. It is divided into two groups: fuels and flows. Fuels encompass nuclear materials (such as uranium) and fossil fuels such as coal, oil and natural gas, while flows refer to energy from natural

movements such as wind, solar radiation, ocean tides, geothermal energy, and river currents (Andrews et al., 2011; Michaelides, 2012). Typically, these primary energy sources need to be converted into secondary forms such as electricity and petroleum products (diesel and heating oil). Even with the growth of renewable energy, fossil fuels (particularly coal and natural gas) still dominate electricity generation.

Due to its combustibility and the heat it releases, coal has been **excavated** from the ground for centuries and used to generate heat by converting its chemical energy (Schweinfurth, 2013). Since the 19th century, coal has been used extensively for various applications such as home cooking and heating (until around 50 AD from cinders in Roman ruins in Britain), in industry and for electricity generation (https://wwf.panda.org/discover/knowledge_hub/teacher_resources/webfieldtrips/climate_change/coal ; Životić et al., 2024). Furthermore, coal is a practical choice due to its affordability and global abundance, as it is the second largest energy source in the world and the most important fuel for electricity generation. According to recent studies (Hendryx et al., 2020), coal is responsible for around 38% of global electricity generation (IEA, 2007; IEA, 2013; IEA, 2019) and around 28% of electricity generation in the USA (EIA, 2019). China and the USA are the largest consumers of coal-fired electricity, accounting for 58% of total global consumption (IEA, 2018). Globally, hard coal and brown coal (54.53%) surpass all other types of non-renewable energy resources (BGR, 2024) such as conventional oil (18.1%), conventional natural gas (17.77%), unconventional oil (6.99%), uranium (1.43%) and non-conventional natural gas (1.18%) (Fig. 1).

In 2016, coal cause around 44% of global CO₂ emissions, surpassing both oil (~35%) and natural gas (~20%) (IEA (2018). Coal is therefore an important factor in climate change. The problem is exacerbated when we consider the annual global CO₂ emissions from coal combustion, which are around 15 billion tons (IEA, 2021). These substances can undoubtedly damage ecosystems, water resources and air quality.

Economic incentives cause key players in the coal sector to resist change, while governments often support coal for the tax revenue and jobs it provides (Yang and Cui, 2012). These elements contribute to enduring use of coal, which is exacerbated by limited access to modern, clean energy in many regions. Coal-fired power stations provide cost-effective, reliable and consistent energy which is crucial to addressing energy poverty. While wealthier countries are looking to phase out coal, it remains vital to the development of less affluent countries. China, the world's largest coal producer and consumer, has set itself the goal of limiting its coal consumption. To move away from coal by 2050, viable alternative energy sources are needed. Ultimately, tackling the problems with coal requires careful consideration of the economic benefits, environmental preservation and the urgent need for alternatives to fossil fuels.

The aim of this paper is to provide basic information on coal exploitation and the environmental and human health impacts of coal use in industry.

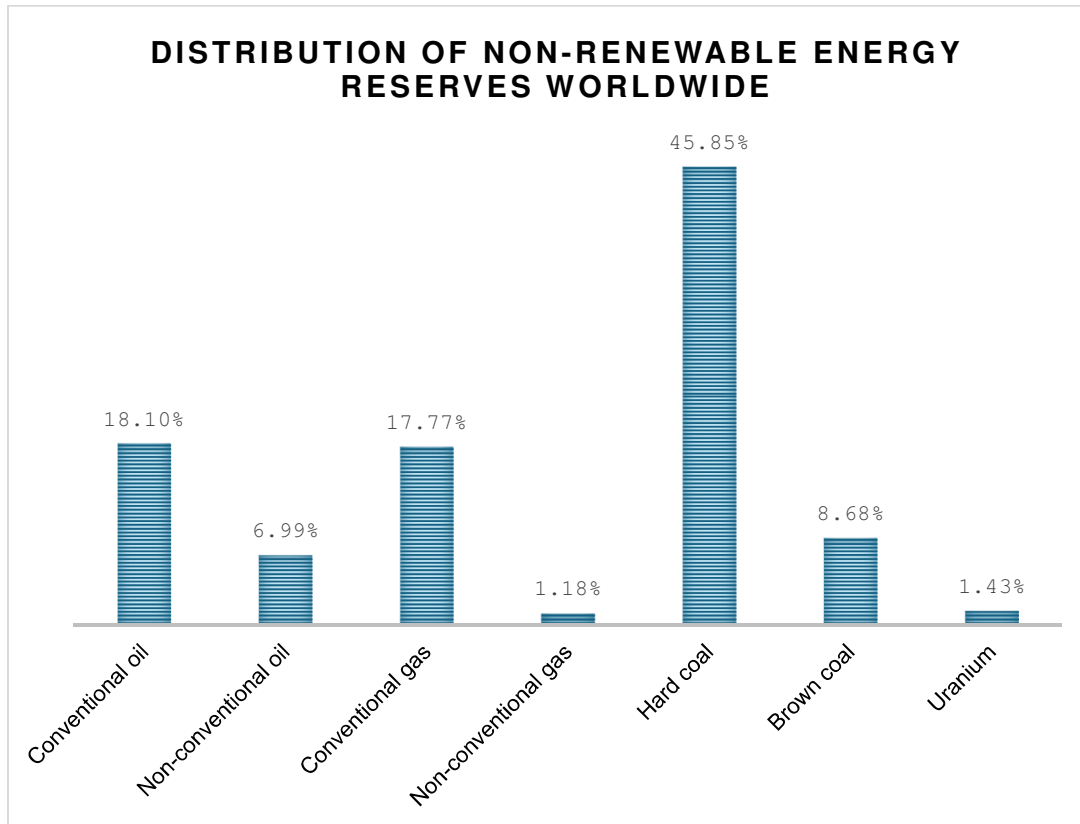


Fig. 1 Global abundance of non-renewable energy reserves (data status 2022) (available data from BGR, 2024).

Coal mining and its impact on the environment

There are two main methods of coal mining: surface (or open pit) mining and underground mining. Surface mining is the preferred method for most low rank coals and when the coal seam is less than 100 meters below the surface. In this technique, the uppermost layers of soil and rock, known as overburden, are removed to expose the coal seams below. Another variant of open-cast mining is mountaintop removal, in which the top of a mountain is excavated to reach the coal seams. Once the coal is extracted, the altered landscape is often filled in with topsoil and replanted with grass and trees. Compared to its underground counterpart, surface mining is less costly.

Underground mining, also known as deep mining, is the method of choice for the extraction of medium and high-grade coal located more than 100 meters below the earth's surface. These mines can be very extensive, reaching hundreds of meters into the earth, with branching tunnels that can extend for kilometers from the central vertical shafts. To access the coal, miners descend into these deep shafts using elevators and navigate in small trains through the extensive networks of tunnels. Large machines are used to extract the coal from these depths.

The choice of mining methods is primarily influenced by the geological characteristics of the coal deposit and the price of coal. While underground mining accounts for around 60% of global coal output, surface mining predominates in some major coal-producing countries, accounting for 80% of Australian production and 67% of US production (Mitra and Saydam, 2013).

Coal, often regarded as the most environmentally damaging energy source, poses a major challenge throughout its life cycle. The environmental impact relates to disturbances caused by engineering activities during coal mining and processing. From mining to transport, stockpiling, processing and

utilization, coal leads to a range of impacts and pollutants that contaminate the air, water and soil (Mamurekli, 1997; Mamurekli, 2010). The environmental consequences of coal mining are multifaceted and vary depending on the mining method and proximity to the mining sites. The direct mining-related impacts are manifold. In addition, changes in groundwater levels and flow patterns often occur near mining areas (Mamurekli, 1997), while hydrology is altered by changes in adjacent hydrological systems. Perhaps one of the greatest impacts of coal mining is the massive change in the landscape that affects the surrounding area.

Coal mining also leads to the release of contaminated water and solid waste products (Fig. 2). Not to be neglected are the significant amounts of pollutants generated throughout the life cycle, from the coal mine to the coal-fired power plant to the waste disposal site. These pollutants affect air quality, water and soil.

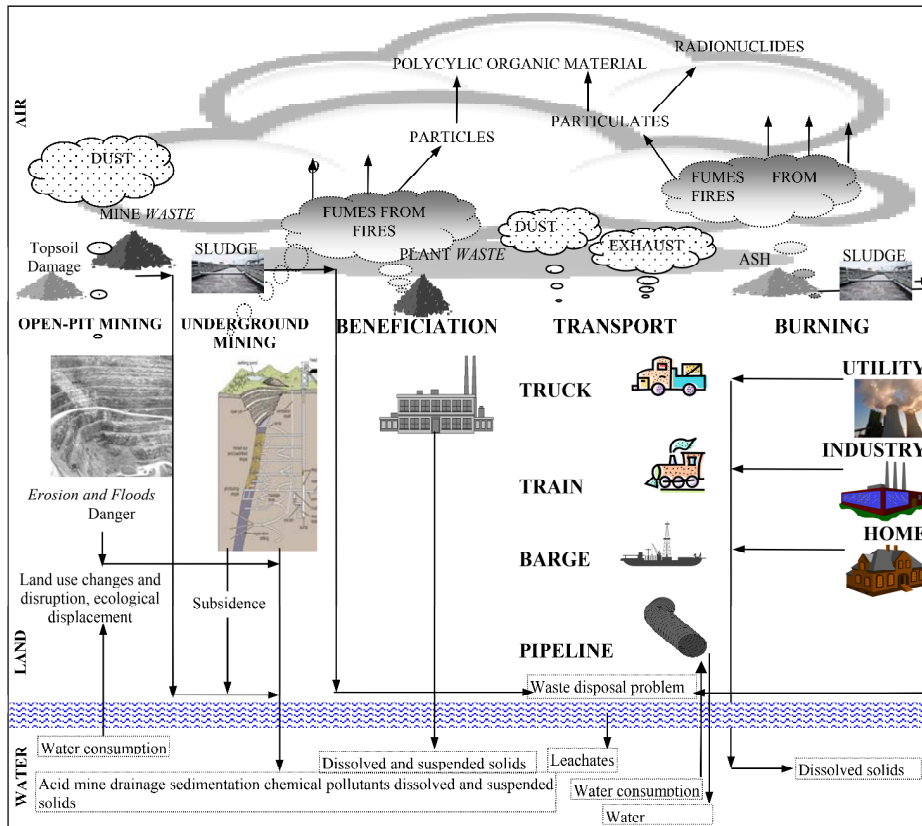


Fig. 2 An illustration of the environmental impacts resulting from coal mining and its utilization processes (Mamurekli, 1997).

Coal mining requires the temporary destruction of vast areas of land, leading to various environmental problems such as soil erosion, airborne dust, noise pollution, water contamination and adverse effects on local wildlife (Mohapatra et al., 2012; Goswami, 2015). When mining operation is established, it invades and destroys large areas of wilderness, displacing native fauna and taking away their habitat and food sources. This leads to an unbalanced ecosystem and even to the endangerment or extinction of entire species.

The most noticeable impact is the alteration of landforms and land use, which leads to a change in the visual landscape. This often results in habitat destruction, noise pollution, dust, vibrations, chemical leaks, erosion, sedimentation, and abandonment of the coal-mining site. Coal excavation can significantly affect natural habitats such as forests and cause irreversible damage to the landscape

(<https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/Wald/WWF-Studie-Extracted-Forests.pdf>) (Fig. 3).

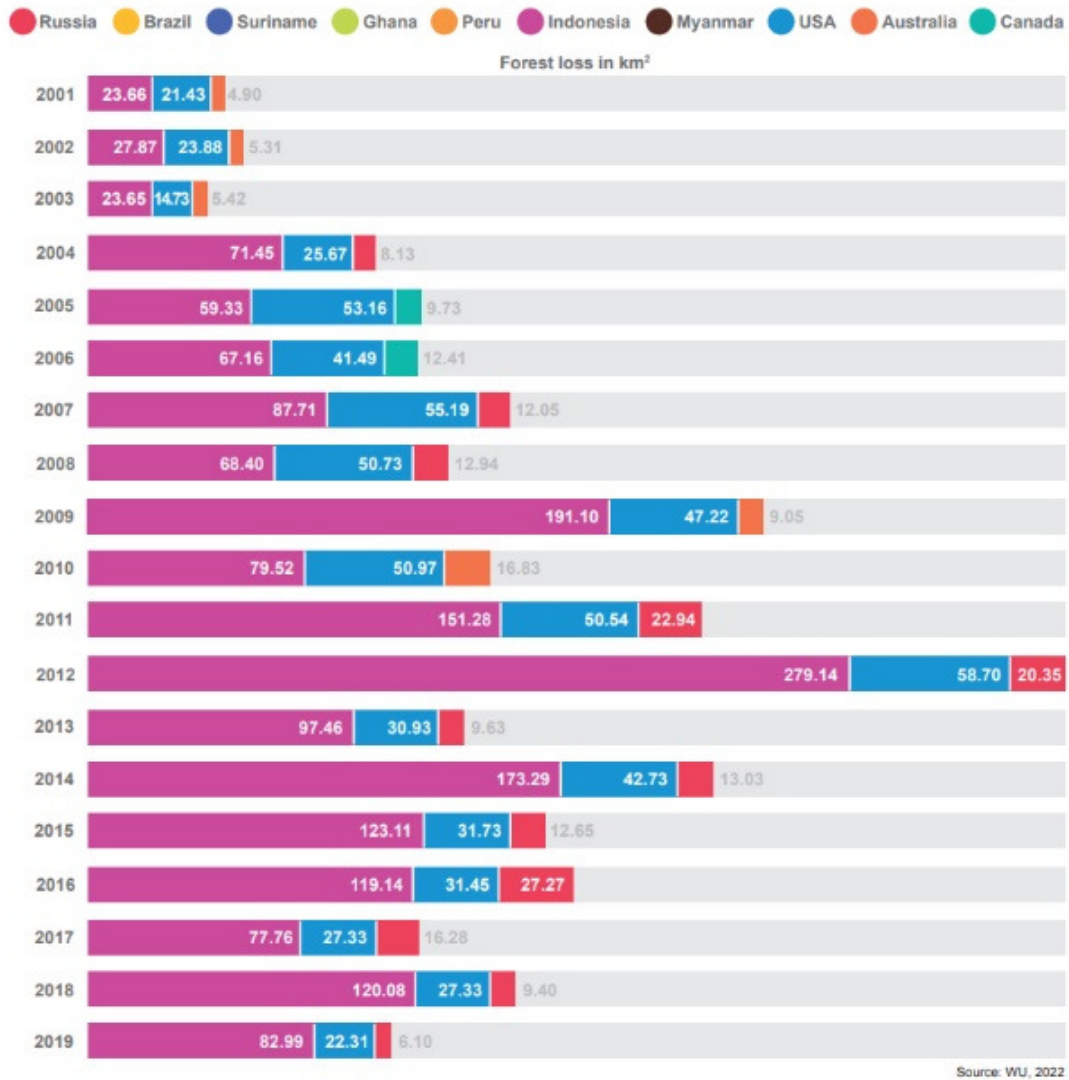


Fig. 3 Forest loss (in km²) induced by coal mining worldwide from 2001 to 2019, by country (according to Vienna University of Economics and Business, 2022: <https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/Wald/WWF-Studie-Extracted-Forests.pdf>).

Global coal production of around 8 billion tons (average value of recent years) generates a lot of waste material from mining (overburden and interburden rocks). According to the IEA (2021), coal mining disposes of more than 12 billion tons of waste material every year. This means that the extraction of coal and mining-related waste per year have a severe impact on geomorphological features, plant and animal habitat and the environment as a whole. Chemical waste and physical hazards such as unused shafts, boreholes and tunnels can also lead to soil degradation. Large quantities of mine waste, which is often flammable, pose a risk of spontaneous combustion. These wastes can also leach potentially toxic elements (As, Cd, Pb, Hg, Zn, Cu, etc.) into nearby water bodies, potentially accumulating in the aquatic food chain and affecting living organisms. The production of toxic waste known as “slurry” from coal mining and processing necessitates the construction of dams, which have failed in the past and caused catastrophic flooding and environmental disasters. However, modern mining practices, including strategic planning and environmental stewardship, aim to reduce the environmental footprint of mining and protect biodiversity (Mamurekli, 2010).

Cascading environmental impacts occur when coal mining disturbs sensitive natural systems (WHO, 1980). These impacts begin with mining of rock masses that disrupt the natural balance and trigger a chain of reactions within the system. For instance, coal mining can lower the water table, reducing the pressure that supports the overlying rocks, potentially causing land subsidence and sinkholes. Such cascading effects can be far-reaching, affecting areas well beyond the mining site and persisting long after mining operations have ceased.

Coal mining is intensely noisy as it is continuous and may disrupt the lives of local residents for decades, resulting in considerable noise pollution. The primary sources of noise in mining operations are earth-moving and processing machinery as well as blasting. Public complaints against the mining industry often focus on blasting noise, followed by problems such as vibration, air pressure shockwaves, pollution and flying debris. The effects of this noise depend on the source, the surrounding topography, land use, vegetation cover, weather conditions, noise's beat, rhythm, and pitch, along with the distance from the source (WHO, 1980). Blasting noise typically escalates with the quantity of explosives used, atmospheric conditions and proximity to the blast site, with closer areas being more affected. Additionally, people's reactions to blasting noise can vary greatly (Mkpuma et al., 2015). Noise pollution can be controlled by the selection of suitable machinery, insulation and acoustic barriers. In this direction, revegetation of buffer zones can help to reduce noise emissions and lessen the visual impact of mining on the surrounding communities.

Seismic activity triggered by mining can destabilize slopes in both underground and surface mines, posing a significant risk to miners and the environment. Mines in areas prone to seismic activity are particularly at risk. The detonation of explosives for blasting can trigger earthquake-like events that can lead to the collapse of mine structures, the entrapment or fatalities among miners, flooding and damage to surface buildings (Scott, 2012).

Dust is a highly visible and ubiquitous problem in coal mining, often causing more concern than its actual impact on health and the environment. Dust can be generated by various activities such as excavation, haul road transport and blasting, or by specific sources such as drilling, crushing and screening (Momoh et al., 2013; WHO, 1980). Factors that influence the generation and impact of dust include the type of rock, moisture levels, local air quality, wind patterns, scale of operations, proximity to the source and other dust-producing activities in the vicinity (Howard and Cameron, 1998). Dust concentrations and their potential effects generally decrease with distance from the source. Inhalation of mine dust can lead to respiratory diseases, including fibrotic diseases that damage lung tissue, such as pneumoconiosis and silicosis, and obstructive ailments that impede airflow, such as bronchitis, emphysema and asthma. Dust reduction can be achieved by moistening roads, stockpiles and conveyor systems and by using dust collectors. Spraying with water is a common practice to curb dust release.

Another environmental threat posed by coal mining is the fires that can occur, as coal is combustible. If a fire breaks out in a coal bed, it can drag on for years or even decades, potentially spreading and releasing harmful fumes into the environment.

Significant amounts of methane are released throughout the mining process. Methane is a potential greenhouse gas that plays a role in the depletion of the ozone layer. **Coal mining releases large quantities of methane into the atmosphere. However, there are also positive examples, such as China, where 56 coal mines with high methane content have released approximately 101.94 million cubic meters of methane, some of which is used for electricity, civil fuels and industrial purposes, while around 39% continues to be released into the air.**

Acid mine drainage (AMD) is metal-enriched water produced by the interaction between water and rock containing sulfur-rich minerals such as pyrite (FeS_2) during the exploitation. The combination of water and natural weathering processes leads to runoff and acidic discharges that can cause significant damage to the environment. The contact between the coal enriched with sulfide minerals (pyrite) and the oxygen-rich environment (air and water) influences the oxidation of Fe^{2+} ions leading to formation of Fe^{3+} -oxide hydrates and sulfuric acid (Scholz and Kahlert, 2015; Scholz and Kahlert, 2019). As the acidic water filters through the coal, it dissolves metals and creates a harmful flow typically rich in aluminium, iron, and sulfate (Costello, 2003; Pagan et al., 2003; Johnson and Hallberg, 2005; Akcil and Koldas, 2006). Typical pH value of the coal drainage water ranges from 2.5 to 4.5 whereas the typical concentrations of Al, As, Cd, Cu, Fe, Pb, Mn, Ni, Zn (Zeng et al., 2023) are listed in Table 1. The process of coal washing produces similar environmental challenges. Careful mine planning can prevent water contact with acid-forming materials (Mamurekli, 1997). In this context,

there are several approaches to predict, avert, and reduce AMD at mining locations. Advances in the prediction of AMD include the development of software, chemical assessments and acid-base calculations to determine the likelihood of AMD formation. It is important to note that not all mining activities that encounter sulfide-rich rocks result in AMD (Mkpuma et al., 2015). This is because the mined ore may be rich in acid-neutralizing minerals such as lime, calcite, carbonate or bicarbonate.

The various modes of coal transport, including trucks, trains, ports, and barges, contribute to air and water pollution. The environmental footprint of coal transport is considered moderate and is related to energy consumption for loading and unloading machinery, water consumption for dust control and accidental spillage from railcars conveyor belts, and docks. The adoption of clean coal technologies helps to curtail emissions of particulate matter (PM), production waste, trace elements, and gases such as NO_x, SO_x and CO₂, thereby mitigating the adverse impacts of coal production and utilization (Osborne and Earl, 1975; Kohl and Nielsen, 1997; Hanif et al., 2020). Advances in the efficiency of coal combustion for power generation have led to a remarkable reduction in CO₂ emissions (Mamurekli, 2010).

Table 1. Typical concentrations of metal ions in coal drainage water (Zeng et al., 2023)

Chemical element	Typical concentration range
Aluminum (Al)	0.5–10 mg/L
Arsenic (As)	0.01–0.1 mg/L
Cadmium (Cd)	0.005–0.05 mg/L
Copper (Cu)	0.01–0.5 mg/L
Iron (Fe)	10–100 mg/L
Lead (Pb)	0.01–0.1 mg/L
Manganese (Mn)	0.1–5 mg/L
Nickel (Ni)	0.01–0.5 mg/L
Zinc (Zn)	0.1–5 mg/L

Mining can also lead to economic inequalities and discontent within communities (Hilson, 2003; Gbadebo et al., 2012). Those employed in organized mining activities tend to earn more than others, which can foster frustration among less affluent community members (Mkpuma et al., 2015). In addition, mining often requires the removal of buildings, structures, and vegetation, not only within the designated mining area, but also in the surrounding regions needed for waste dumps and related activities. This leads to the displacement of communities residing in these areas.

Coal mining often disrupts the livelihoods of ethnic communities that rely on the land, as areas designated for mining activities are stripped away for coal extraction. This results in the loss of the traditional means of subsistence for these groups (Bian et al., 2010).

The demographic composition of mining regions is altered primarily because the labor force required for mining operations – usually managers, skilled and semi-skilled workers — is being recruited from outside the local ethnic communities, which often lack such trained individuals. Additionally, the influx of traders and other non-local populations into mining areas over time causes significant shifts in local demographics. This can dilute the presence and influence of indigenous ethnic groups and affect their cultural and religious practices, and lead to gender imbalances. Even after mining activities cease, the population may decline rapidly, but the long-term effects on the community remain.

In remote mining locations, the introduction of mining operations can lead to socio-economic conflict and an increase in the cost of living. Employment opportunities for women, impoverished people and youth can improve their financial opportunities, which in turn affects their social and cultural norms. Communities traditionally dependent on agriculture and forestry tend to be less economically developed. However, the introduction of industrial activities in these areas can exponentially boost economic activity and increase the general prosperity and purchasing power of the population. This surge in economic prosperity often leads to a higher cost of living, which has a negative impact on ethnic groups not involved in mining-related work.

The health impacts caused by coal mining are diverse and extensive. The wellbeing of people living near mining sites is compromised by pollution, imposing various costs to the community when trying

to limit environmental damage. Workers in the mines and associated facilities are also prone to occupational health issues, such as skin diseases, respiratory illnesses, and hearing loss. Further details about the health impact and related consequences will be elaborated in a separated chapter below.

One of the very positive post-mining activities is the “conversion” of many exhausted coal open-pit areas in eastern Germany into lakes with high recreation value (<https://earthobservatory.nasa.gov/images/148031/from-mine-district-to-lake-district>). These developments have also given rise to new challenges. During pit-mining, the water level was considerably lowered; when it was subsequently raised to create lakes, the water came into contact with excessive pyrite deposits, resulting in the production of large amounts of sulfuric acid and iron oxide-hydrates, which contaminate nearby rivers, such as the River Spree. These brown oxide hydrates settle on aquatic plants, causing them to perish (Friedland et al., 2021).

Sustainable development is often defined as meeting current needs without jeopardizing the ability of future generations to meet their own needs. It involves the integration of economic activities with environmental responsibility, societal welfare and robust governance. These principles have increasingly shaped environmental and social policy in recent years and are endorsed by international organizations such as the United Nations and the World Bank (Dann and Riegner, 2019).

Advances in technology and scientific research can now lessen the environmental toll of mineral extraction and limit the effects to a level that is not detrimental to the environment. By adopting conscientious operating methods and utilizing the latest engineering innovations and technologies, the impact of mining can be controlled, mitigated and confined to the immediate vicinity of the extraction site. Mining practices are becoming more environmentally sustainable and aim to minimize the impact on the environment and rehabilitate mining sites for future use by communities or natural ecosystems.

Coal is the most harmful fossil fuel to the environment, releasing more carbon than any other energy source. Burning coal causes severe damage to the land, air and water and leads to global warming and climate change. Scientists around the world have pointed to human activity as one of the major causes. To combat climate change, the Paris Agreement was signed by 197 countries around the world and has since been ratified by more than 140 countries (UNFCCC, 2017). The Agreement aims to limit the global temperature increase to no more than 2°C above preindustrial levels in order to protect the world’s population from worsening climate impacts on human health, livelihoods and the environment. As there is a direct link between the burning of fossil fuels, CO₂ emissions, and the increase in global average temperature (IPCC, 2013), humanity must strive to rapidly reduce greenhouse gas emissions from the burning of fossil fuels and limit the temperature increase to less than 2°C.

Combustion products of coal

Over the past two centuries, the coal of different rank and grade has been used mainly as a source of heat and power in households and industry, and later to generate electricity. Combustion technologies have changed significantly from the late 1800s to the present day (Miller, 2016). The implementation of new standards and stringent environmental controls in recent decades has influenced the development of more efficient clean coal combustion technologies, better compliance with standards and lower gas emissions (CO₂, SO_x, NO_x) as well as the production of combustion residues or by-products of coal combustion (Robl et. al., 2017; Hagemeyer et al., 2019). Coal combustion residues are waste materials composed of three types of ash (bottom ash, boiler slag and fly ash) and flue gases. Bottom ash composed of melted and/or newly formed minerals left over from the combustion process. It consists mainly of Si, Al, Fe, Ca, and Mg, with a low content of other elements (Robl et. al., 2017; Životić et al., 2024). In addition to Si, Al, Fe, Ca and Mg, fly ash contains low concentrations of Na, K and P. As, Be, B, Cd, Cr, Co, Ga, Pb, Mn, Hg, Mo, Se, Sc, Tl and V as well as dioxins, PAHs and other carbon compounds occur in very small quantities (traces; expressed in ppm) in fly ash (Fig. 4). The chemistry, in particular, the trace elements of both ashes, depends on the mineral and maceral composition of the coal, the coal rank and the combustion conditions. The flue gas consists mainly of nitrogen, carbon dioxide and water vapor. Modern technologies in coal-fired power plants use a number of technological methods to remove SO₂ and oxides from the flue gases, known as flue-gas desulfurization (FGD). The main product of FGD is “synthetic” gypsum and spray dryer absorbents.

Annually, the mining industry generates billions of tons of solid waste worldwide. It is influenced by the mining method, type of ore, geological context and processing techniques (Kiventerä, 2019). The majority of coal combustion products are disposed of in ash ponds, while only 10 to 15% are used in the ceramics and construction industries, wastewater remediation, soil improvement, catalysis, recovery of metals (REEs) and material synthesis (Zhou et al., 2022; ACAA, 2023; Dai et al., 2014; Dai and Finkelman, 2018; Dong et al., 2020; Gollakota et al., 2019). In some cases where waste ponds are improperly constructed, this can affect the contamination of ground and surface water with toxic elements such as As, Cd, Ba, Tl, Se and Pb (Chen et al., 2024).

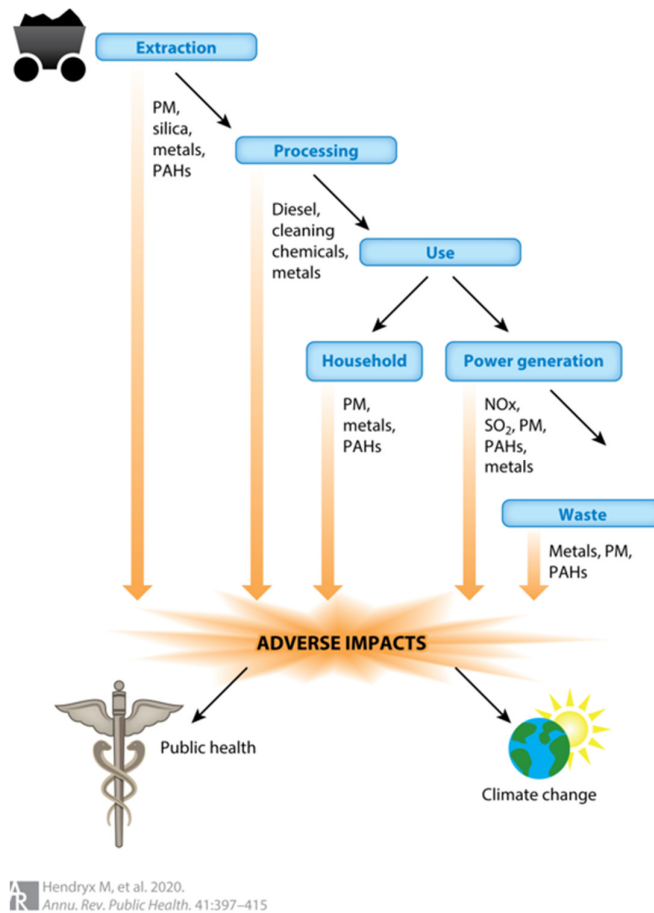


Fig. 4 The coal use continuum and its impacts (Hendryx et al., 2020, licensed under CC BY 4.0).
Abbreviations: *NO_x*-nitrogen oxides; *PAHs*-polycyclic aromatic hydrocarbons; *PM*-particulate matter; *SO₂*- sulfur dioxide.

Pollutants from coal combustion have a profound impact on public health, especially on vulnerable groups such as children, the elderly, pregnant women and individuals with respiratory conditions in urban areas. The adverse health effects of coal include cardiovascular and respiratory diseases as well as developmental impairments in the brain and nervous system. However, the negative health effects of coal-fired power generation were analyzed by Jensen (2013). In the study, for every TWh (Terrawatt-hour) of coal-fired electricity in Europe, serious illnesses such as hospital admissions, heart failure and chronic bronchitis as well as minor illnesses were reported. The more serious consequences for human health were found in power stations burning lignite (Markandya and Wilkinson, 2007). Proximity to coal-fired power plants and factors such as weather conditions and local geography influence exposure to emissions. These emissions have the potential to travel long distances,

affecting the health of populations far from the source. Vulnerability to the health impacts of coal emissions varies depending on individual factors such as age, health status, and medication use. Children, the elderly, pregnant women, and individuals with respiratory conditions are particularly at risk from air pollution.

Health effects of the use of coal

Respiratory effects

Air pollution was defined back in 1979 by the United Nations Economic Commission for Europe as: *The introduction by man, directly or indirectly, of substances or energy into the air resulting in deleterious effects of such nature as to endanger human health, harm living resources and ecosystems and material property and impair or interfere with amenities and other legitimate uses of the environment* (UNECE, 1979; Barreira et al., 2017). It is caused by the emission of various gases (such as carbon monoxide, carbon dioxide, nitrogen oxides and sulfur dioxide), particulates and liquids from diverse origins that accumulate in the air. Predominant contributors to air pollution are inefficient transportation, domestic burning of fuel and waste, emissions from coal-powered stations and industrial processes (Barraza-Villarreal et al., 2008). Air pollutants primarily affect the lungs (Marino et al., 2015), as inhalation of contaminated air is the ninth leading cause of death related to heart and lung conditions (Kurt et al., 2016). In particular, combustion of coal causes negative health effects on the respiratory system (especially the lungs) through emitted air pollutants such as particulate matter (PM), sulfur dioxide (SO₂) and nitrogen oxides such as NO₂. Pollutants directly damage the human respiratory tract and lungs by damaging cells through oxidative molecules (Rückerl et al., 2011; Pope and Dockery, 2006; US EPA, 2024; Myllyvirta, 2013) (Fig. 5). Prolonged exposure to coal dust, especially in miners, leads to severe lung diseases such as silicosis, pneumoconiosis, emphysema, chronic bronchitis, asthma, lung cancer, and respiratory infections (Laney and Weissman, 2014; Perret et al., 2017; Gasparotto and Da Boit Martinello, 2021). As several studies show (Gao et al., 2013; Raaschou-Nielsen et al., 2013; Gauderman et al., 2015; Kurt et al., 2016), even indirect contact with coal dust can cause chronic obstructive pulmonary disease, asthma, lung cancer and respiratory infections, which particularly affect children and the elderly.

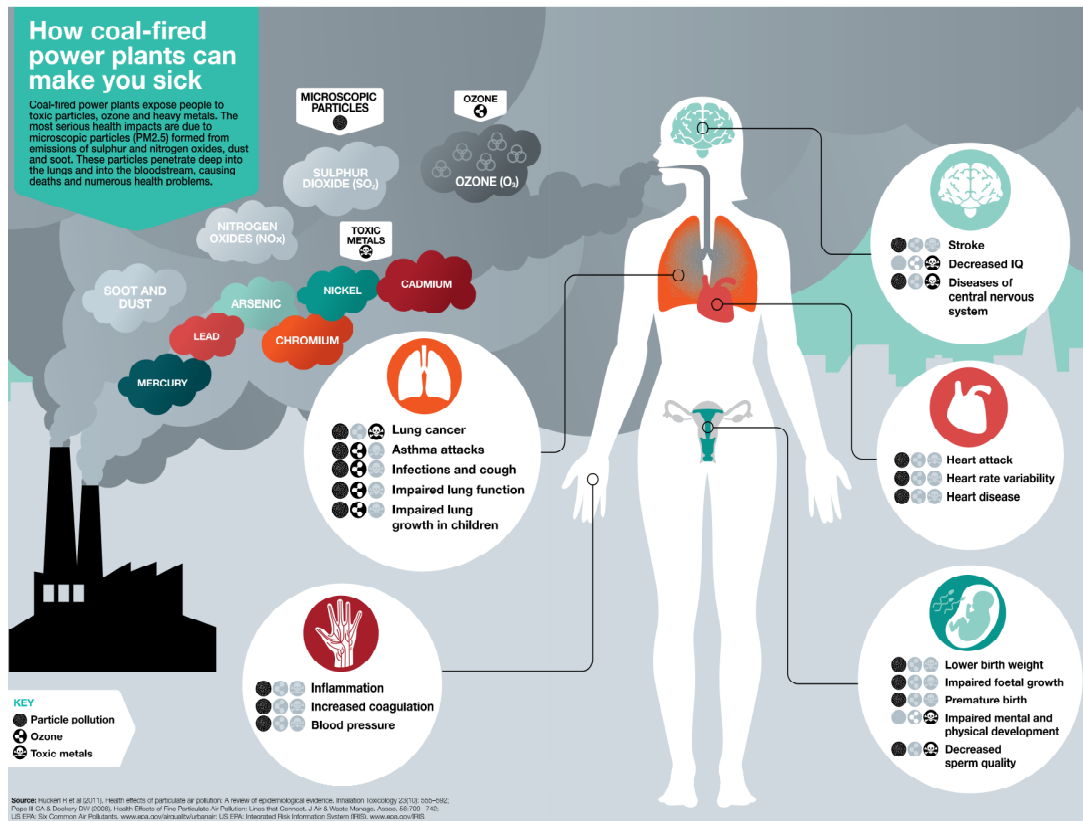


Fig. 5 Health effects due to use of coal (<https://www.greenpeace.org/static/planet4-slovenia-stateless/2019/03/a6c2187b-a6c2187b-silent-killers.pdf> from Myllyvirta, 2013).

The following pollutants are of particular importance for respiratory health and have particularly severe consequences:

Carbon monoxide (CO) is an odorless, colorless, tasteless, **highly flammable and highly toxic** gas. It is produced as a by-product of incomplete combustion of fossil fuels such as gasoline, automated vehicles, aircraft, the wood used in boilers, natural gas emissions, coal, mines, gas fires, industrial waste, sewage leaks, solid fuel appliances, water heaters, and open fires, as well as other natural processes and substances on the earth's surface (Salehabadi et al., 2023). While the overall atmospheric CO concentration reaches 0.1 ppm as a background level in the atmosphere, urban areas see levels of 1-10 ppm, high-traffic areas can reach up to 50 ppm, and coal combustion in power plants can lead to even more alarming concentrations of 50-300 ppm (Xie, 2015). Inhaling even small amounts of this gas can cause confusion, dizziness, headaches, nausea, weakness, and fainting. However, prolonged exposure can lead to damage to the nervous and cardiovascular systems and cause neurological and heart-related changes.

Another product of fossil fuel production is carbon dioxide (CO₂), a colorless, odorless and non-flammable gas. Inhaling high concentrations of CO₂ can lead to rapid breathing, rapid heartbeat, unconsciousness, and headaches, while prolonged exposure can significantly disrupt the human metabolism.

Burning coal generates PM, including fine particles with a diameter of 2.5 micrometers (PM2.5) and even smaller, as well as larger particles up to 10 micrometers (PM10). Due to their miniscule size, PM2.5 can penetrate deep into the lungs and cause respiratory distress, asthma and impaired lung function, leading to more hospitalizations for infections and chronic obstructive pulmonary disease (Hagemeyer et al., 2019). The study by Gasparotto and Da Boit Martinello (2021), based on global epidemiological data, showed significant respiratory impacts in communities exposed to PM2.5. Long-term exposure to PM2.5, even at low concentrations (Barreira et al., 2017), is also associated with the development of lung cancer, especially when highly toxic substances such as polycyclic aromatic

hydrocarbons are present on the surface (Raaschou-Nielsen et al., 2013). At this point, we would like to emphasize that NO_x and SO_2 are precursors that form secondary PM in the atmosphere, which often pose a greater health risk than the primary PM itself, which is produced during coal combustion. Yi et al. (2006) have shown in their study on total PM emissions due to coal combustion in Chinese power plants that the ratio $\text{PM}_{10}:\text{PM}_{2.5}$ is between 10:1 and 3:2.

Sulfur in coal occurs mainly as a component of pyrite (FeS_2) and organically bound sulfur. Other forms of sulfur (sulfate and elemental sulfur) are usually trace components of coal. Regardless of the form in which it occurs, sulfur is generally oxidized during coal combustion and forms various gaseous sulfur oxide compounds. Sulfur dioxide, a by-product of coal-burning power plants, can be absorbed in the nasal passages and converted into sulfuric acid, causing a burning sensation. This sulfuric acid can also adhere to dust particles that are inhaled, leading to serious respiratory problems.

The presence of SO_2 exacerbates respiratory symptoms in residents, especially children with asthma, adults over the age of 65 and people with chronic lung-related illnesses (US EPA, 2008a). Even low concentrations of SO_2 are associated with an increased mortality risk from heart and lung conditions. Studies in European cities have shown that even low SO_2 concentrations (less than 10 ppb on a 24-hour average) are associated with an increased risk of death from heart and lung conditions (US EPA, 2008a). For every 10 ppb increase in SO_2 concentration, there is a 0.4 to 2% increased risk of death. Fortunately, SO_2 concentrations in air have decreased in many countries in recent decades due to the implementation of pollution control technologies in coal-burning power plants. However, countries with lower pollution standards are exposing their populations to health risks from SO_2 . In China, for example, SO_2 concentrations in air increased by 7.3% annually from 2000 to 2006, primarily due to emissions from power plants. However, a policy change in 2005 led to increased use of flue-gas desulfurization (FGD) technologies, and SO_2 concentrations have since declined (Lu et al., 2010).

Sulfur dioxide can be absorbed by the lining of the nasal passages and converted into sulfuric acid, causing a burning sensation. It can also coat dust particles that are inhaled, leading to severe respiratory problems (Fig. 6). The resulting acids can corrode or decompose materials such as limestone, marble, iron, and steel, leading to the deterioration of building facades and monuments. This is a global problem. When sulfur oxides are washed out of the air by precipitation (acid rain), they can acidify lakes and soils and damage or kill plants and animals. There are several methods to reduce sulfur emissions from coal combustion. These include physically removing pyritic sulfur from coal prior to combustion, cleaning combustion gases to remove gaseous sulfur compounds before they are released into the atmosphere, and switching from high sulfur coal to low sulfur coal or other fuels.

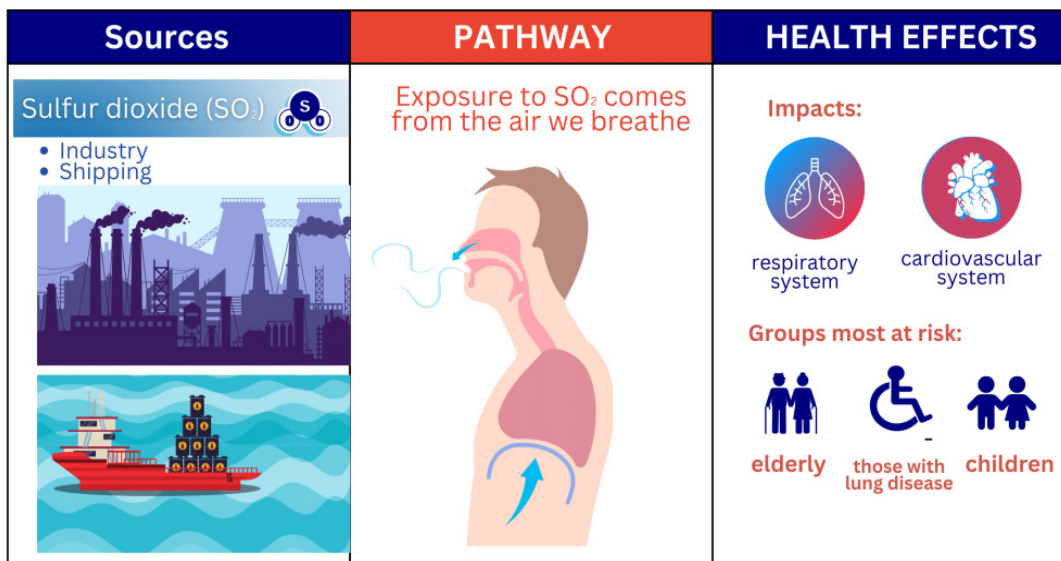


Fig. 6 Sources, pathway and health effects of SO_2 (<https://sigmaearth.com/astonishing-facts-about-sulfur-dioxide-what-you-need-to-know/>).

The main techniques for removing sulfur dioxide (SO₂) from coal-burning flue gases mainly rest on two pillars: non-regenerative and regenerative techniques. The non-regenerative techniques are wet scrubbing with lime or limestone, spray-dry scrubbing and dry sorbent injection (Hanif et al., 2020). Wet scrubbing with lime or limestone as a process begins when flue gasses are passed through a slurry of lime (Ca(OH)₂) or limestone (CaCO₃). In such a process, SO₂ reacts with the alkaline slurry to form calcium sulfite (CaSO₃) and calcium sulfate (CaSO₄). The by-products of this process can be disposed of or used in other applications (Kohl and Nielsen, 1997), such as gypsum for construction (gypsum plaster and gypsum boards). In the so-called spray-dry scrubbing process, when a fine mist of lime slurry is sprayed into the flue gas stream, causing the SO₂ to react with the lime, and the resulting dry particles are collected in a particulate control device (Kohl and Nielsen, 1997; Hanif et al., 2020). When dry powdered lime or other alkaline materials are injected directly into the flue gas stream and the sorbent reacts with SO₂ to form solid compounds that are then removed by particulate control devices, this is referred to as a dry sorbent injection process (Hanif et al., 2020). There are three basic approaches to regenerative techniques (Wellman-Lord process, activated carbon adsorption and ammonia-based processes). In the Wellman-Lord process (Osborne and Earl, 1975), SO₂ is absorbed in an aqueous solution of sodium sulfite (Na₂SO₃) and forms sodium bisulfite (NaHSO₃). Regeneration is achieved when such a solution is heated to release SO₂ gas, which can be recovered and used to produce sulfuric acid or elemental sulfur (Hanif et al., 2020). In activated carbon adsorption, the flue gasses pass through a bed of activated carbon that adsorbs SO₂, resulting in regeneration of carbon by heating and releasing concentrated SO₂ for recovery (Hanif et al., 2020). Ammonia-based processes rely on SO₂ absorption in an aqueous ammonia solution and the production of ammonium sulfite, which upon heating releases SO₂ that can also be recovered and reused (Hanif et al., 2020). We must emphasize that these techniques vary in terms of complexity, cost and efficiency, and the choice of method depends on the specific requirements and environmental regulations.

Nitrogen oxides (NO_x), which come from sources such as vehicles with internal combustion engines and coal-fired power plants, interact with chemicals in the atmosphere and together with nitrous oxide (N₂O) and nitrogen dioxide (NO₂) create ground-level ozone (O₃) or smog. Chronic inhalation of NO₂ and ozone can have detrimental effects on respiratory health, making these pollutants a major concern. The US Environmental Protection Agency has highlighted that children with asthma exposed to NO₂ may experience more frequent wheezing and coughing and a marked deterioration in lung function at low concentrations of 0.2 to 0.5 ppm (US EPA, 2008b), while at higher concentrations, 1-2 ppm NO₂, inflammation of the airways is triggered. It is important to highlight that even at ambient concentrations of 3-50 ppb, NO₂ can pose a serious health threat and potentially lead to viral and bacterial infections.

Cardiovascular effects

Studies conducted in both urban and rural areas have shown a clear link between air pollution and a higher likelihood of developing conditions such as coronary artery disease and heart failure, as well as an increased incidence of strokes and overall cardiovascular health issues and deaths (Gasparotto and Da Boit Martinello, 2021). Coal-fired power plants contribute to the global burden of cardiovascular disease primarily through the emission of PM. In particular, inhalation of particles smaller than PM_{2.5} has been linked to cardiovascular disease and death (US EPA, 2009; Bassig et al., 2020; Lockwood et al., 2009) (Fig. 7).

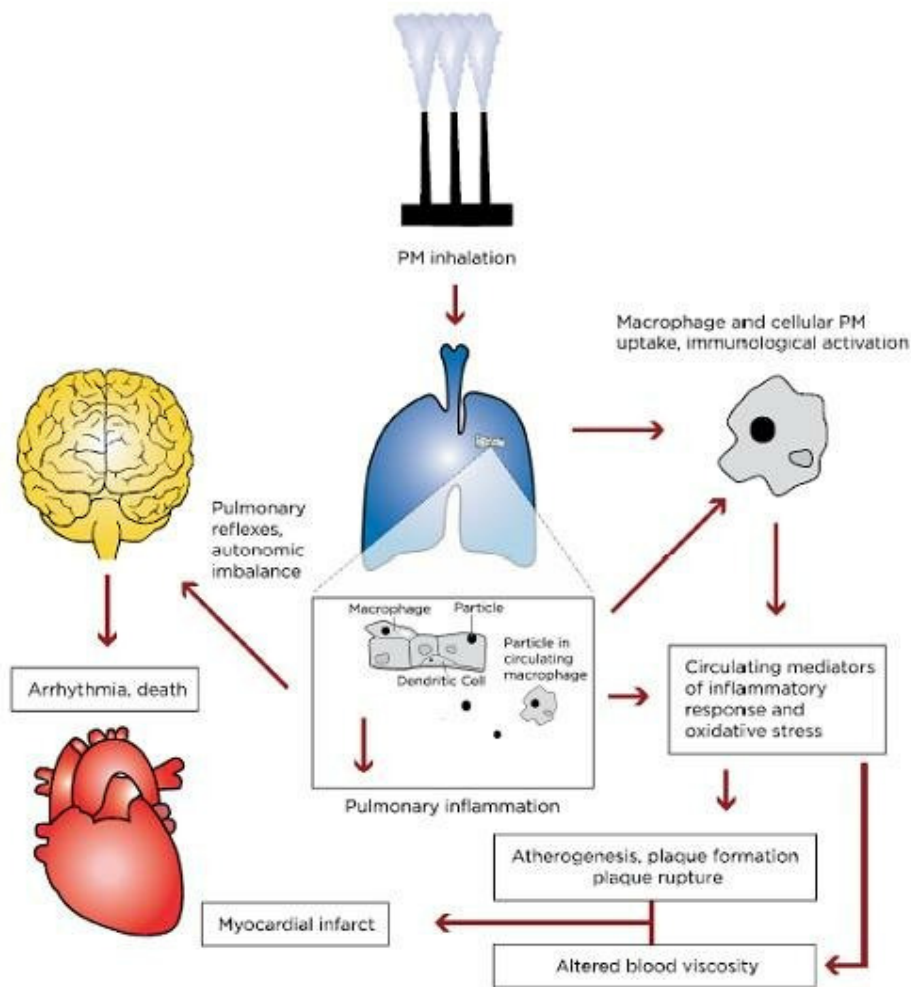


Fig. 7 Mechanisms by which coal pollution causes cardiovascular disease (Lockwood et al., 2009).

Damage to the cardiovascular system follows a similar pathway to respiratory harm: oxidative stress caused by pollutant molecules triggers inflammation and cell damage. Studies by the World Health Organization (WHO) have estimated that outdoor air pollution (in both cities and rural areas) caused 4.2 million premature deaths worldwide in 2019 as a result of fine particulate matter (WHO, 2024). This mortality is due to cardiovascular, respiratory diseases, and cancers. Prolonged exposure to NO_2 , PM_{10} and especially $\text{PM}_{2.5}$ particles is associated with an enlargement of the left and right ventricles leading to an increase in arterial blood pressure (Aung et al., 2018). In this context, we must emphasize that prolonged exposure to fine $\text{PM}_{2.5}$ is scientifically associated with faster progression of atherosclerosis and more frequent hospitalizations for heart-related conditions. The United States Environmental Protection Agency (US EPA, 2009) concluded that most studies show an increase in cardiovascular-related hospital visits of 0.5-2.4% for every $10 \mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ levels. A 2007 review highlighted an 8-18% increase in cardiovascular mortality with each $10 \mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$ (Lewtas, 2007). Additionally, some later studies (Romieu et al., 2012; Liu et al., 2013) confirmed that air pollution can impair cerebral arteries, heightening stroke risk as well as cardiovascular incidents. Emissions from coal-fired power plants not only affect respiratory and heart health, but also contribute to neurological issues in children, fetus growth complications, and cancer risks

Cancer and other chronic diseases

Not only has air pollution been classified as a known human carcinogen, but dust emissions from coal mining can also increase the risk of lung cancer. As the results of the study by Shahadin et al. (2018) show, air pollution has been identified as a first rank carcinogen for humans. It is also known that exposure to coal dust over a long period of time, especially in coal miners (day after day), leads to severe lung diseases that eventually develop into lung cancer (El Safty and Siha, 2013; Laney and Weissman, 2014; Perret et al., 2017; Gasparotto and Da Boit Martinello, 2021) (Fig. 8). Coal fly ash and sludge contain high levels of heavy metals such as arsenic (As) and cadmium (Cd), as well as organic pollutants such as PAHs and dioxins. These substances, which are also released directly from power plant smokestacks, pose a serious risk to major organs such as liver and kidneys and are known to be carcinogenic. The concern escalates with the knowledge that the average uncontrolled coal-fired power plant releases around 110 kilograms of arsenic into the atmosphere every year. This alarming fact underlines the urgent need for effective control measures to curb these dangerous emissions. At this point we would just like to point out, for the sake of magnitude, that arsenic causes cancer in one in 100 people who drink water containing 50 ppb (parts per billion), as found by (Staudt and Bradley, 2011).

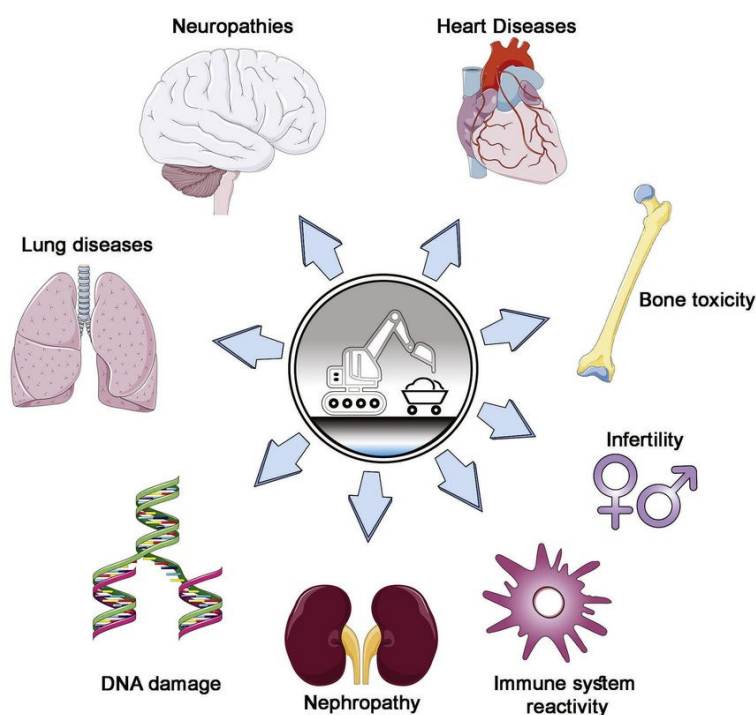


Fig. 8 Various types of chronic diseases (including lung cancer) caused by coal use (Silva et al., 2021).

Reproductive health

Human reproductive functions are impaired by air quality, with environmental contaminants leading to deficiencies in gametogenesis and reduced reproductive capacity in affected populations (Carre et al., 2017). Infertility encompasses both male and female factors (Mahalingaiah et al., 2016) and air pollution, particularly from PM₁₀ and SO₂ emissions from fossil fuel combustion, can impact women's reproductive health, especially the menstrual cycle (Merklinger-Gruchala et al., 2017) (see Fig. 8). Exposure to air pollution is associated with menstrual irregularities and an increased risk of miscarriage. Studies have provided strong evidence that air pollutants such as SO₂, PM, NO₂ and ozone during pregnancy are associated with low birth weight, preterm birth and pregnancy complications (US EPA, 2009; Srám et al., 2005; Mahalingaiah et al., 2016; Barnett et al., 2005; Olsson et al., 2013). In

addition, infant mortality in countries with initially moderate to low rates, such as Chile, China, Mexico, Thailand, Germany and Australia is rising with increasing coal consumption (Gohlke et al., 2011). Over the past half century, male sperm counts have declined, a trend that may be due in part to air pollution (Hallak et al., 2018) and contributes to an overall decline in male fertility (Carlsen et al., 1992). Recent evidence suggests that coal miners have a significant reduction in semen volume and semen viscosity, likely due to long-term exposure (10-25 years) to coal dust containing high levels of lead (Pb) and cadmium (Cd), which negatively impact sperm structure and function (Mohanty and Mahananda, 2015).

Neurological Effects

Numerous neurotoxic elements such as arsenic (As), mercury (Hg), and aluminum (Al) are present in coal and have been extensively documented to induce oxidative stress and cell death in the brain (Schwartz et al., 2018; Mochizuki, 2019) (see Fig. 8). Arsenic, for instance, targets the peripheral nervous system, particularly sensory fibers, leading to painful neuropathic conditions such as anosmia (loss of smell) and ageusia (loss of taste) (Kawasaki et al., 2002; Ahamed et al., 2006), and can also cause axonal degeneration when a lack of thiamine disrupts nerve myelination (Gasparotto and Da Boit Martinello, 2021).

The approximate mean concentration of mercury (Hg) in coal is rather low and amounts to about $0.2 \mu\text{g g}^{-1}$ (Toole-O'Neil et al., 1999). A substantial proportion of the mercury in coal is associated with the presence of pyrite (FeS_2). This is probably due to the removal of mercury with pyrite during the physical process of coal cleaning. Coal-fired power plants are a major global source of mercury emissions, releasing it into the air and water (Munthe et al., 2010). This mercury can contribute to neurodegenerative diseases such as Alzheimer's due to significant trace element imbalances in brain regions such as the amygdala, hippocampus and cerebral cortex (Mutter et al., 2004; Mold et al., 2020). The mercury from these plants is rapidly released into the atmosphere, with some settling in water bodies and being converted into methylmercury, which then enters the aquatic food chain (Lippmann et al., 2003; Gasparotto and Da Boit Martinello, 2021). Consumption of seafood contaminated with methylmercury can cause developmental problems in young children and fetuses, including reduced intelligence, delayed brain and nervous system development, attention disorders and subtle changes in vision, memory and language abilities (Oken and Bellinger, 2008; Boucher et al., 2012). Studies from around the world have found that many women have blood mercury levels above safe limits due to eating contaminated fish and pose a risk to their children (McDowell et al., 2004; Díez et al., 2009; Lam et al., 2013).

Mental health and social damage

Coal projects can also affect mental health (which also affects physical health) and damage the social and economic wellbeing of communities. These mental and social harms may include: distress related to negative health impacts, costs related to environmental damage and declining land values, concerns regarding noise and air pollution, social divisions and inequalities between those who benefit from the coal industry and those who do not, and distress and disempowerment due to asymmetries in power, influence and access to information and resources (Coady et al., 2015).

Radiation and coal

It is a fact that coal contains minute quantities of radioactive elements radium (Ra) and uranium (U) as well as other naturally occurring radioactive isotopes that may contaminate the environment. Upon combustion, coal fly ash can contain uranium and thorium concentrations up to ten times higher than their initial levels (Hvistendahl, 2007). This radioactive ash released by coal plants is absorbed by the local environment and affects both humans and crops. As stated by Janković et al. (2011), coal, like other trace elements, contains certain radionuclides such as uranium (^{238}U , ^{235}U), thorium (^{232}Th), radium (^{226}Ra), potassium (^{40}K), and polonium (^{210}Po), which are released into the environment during

figures reflect direct healthcare expenditure such as medication and hospital visits due to increased illness rates, lost productivity due to absenteeism and societal costs from premature deaths.

In India, health-related expenses due to coal power station pollution are estimated to cost the government between 3.2 and 4.6 billion dollars (Guttikunda and Jawahar, 2014).

In Australia, health damage from coal-fired electricity are estimated at 2.6 billion dollars per year (Beigler, 2009), including the cost of lost work, chronic disease treatment and premature mortality. Specifically, the health-related costs solely from coal power stations in Hunter Valley, Australia are projected at 600 million dollars per year (Armstrong, 2015). In addition, the International Monetary Fund identified that fossil fuels were subsidized to 5.3 trillion dollars in 2015, equivalent to 6.5% of global GDP and exceeding global health spending. Eliminating these subsidies could reduce the number of deaths from outdoor air pollution by 55%, saving approximately 1.6 million lives annually, with coal accounting for 93% of this potential reduction (Coady et al., 2015).

The World Health Organization is committed to reducing emissions from the energy sector and advocates a shift to renewable energy sources such as solar and wind power and improved energy efficiency to reduce the harmful effects of health of air pollution from burning fossil fuels for electricity, transportation, agriculture and other human activities (Hussain and Reza, 2019; WHO, 2020).

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Author contributions

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Data availability

The authors confirm that all relevant data are included in the article.

Declarations

Conflict of interest

The authors declare no competing interests.

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