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Review

A Review of the Impact of Spontaneous Combustion on Slope Stability in Coal Mine Waste Dumps

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Abstract

Mining waste from both underground and open-pit mines is typically placed in surface sites known as mine waste dumps. Over time, as large volumes of mining waste accumulate, these dumps become higher due to the limited surface area allocated to dumping. Ensuring the stability of mine waste dumps is a major concern for both mining operations and local governments due to safety risks to the dumps themselves and their surrounding environments. In some cases of mine waste dump, spontaneous combustion poses a significant challenge, affecting not only the environment but also the slope stability of mine waste dumps. This review synthesizes existing research on the mechanisms of spontaneous combustion, its thermal effects, and the implications for geomechanical stability in mine waste dumps. It also examines methods for monitoring and controlling these processes, identifies gaps in the current research, and suggests directions for future studies. The review also reveals that combustion-induced temperature changes, material degradation, and gas generation significantly impact the geotechnical properties of building material dumps, contributing to slope failure. This review is expected to provide valuable insights that help mining authorities assess risks, minimize impacts, and implement preventive measures to mitigate unexpected spontaneous combustion-induced slope failures in mine waste dumps.

Keywords: spontaneous combustion; slope stability; mine waste dumps; monitoring; mitigation strategy

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1. Introduction

In Poland, mining waste, i.e., rock extracted along with coal, is stored in mining waste disposal facilities in the form of dumps, post-mining waste heaps, or settling ponds. Currently, the accumulation of extractive waste in Poland accounts for over 550 million Mg. A total of 153 such facilities have been identified across the country with a total area of 11,304 ha (Figure 1) [1]. This has pointed out the necessity of overseeing the managers of closed mining waste disposal facilities. This is due to the fact that the extraction of waste and residual coal from dumps disrupts the stability of the facility. Combined with rainfall, this can lead to landslides and, as a consequence—due to air exposure—trigger spontaneous combustion [1–3].

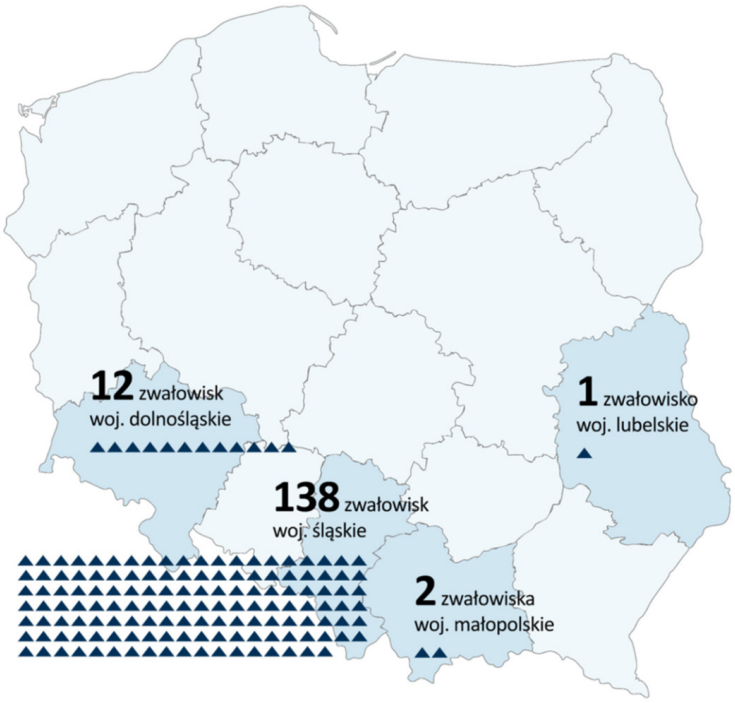


Figure 1. Location of coal mine waste dumps in Poland [1].

The situation is the same in other countries; e.g., according to the Ukraine Mining Ministry, in the area of coal mines closed within the boundaries of three Ukrainian coal basins, 341 spoil piles were inventoried, 105 of which had seats of fire [4]. In the coal basins of China, over 6 billion Mg of waste has been deposited between 1500 and 1700 facilities, with an area of over 15,000 ha [5–8]. Generally, mining waste accumulated on the ground occupies large areas of land, causing many environmental and safety hazards, including vegetation damage, water and soil loss, air and groundwater pollution, spontaneous combustion and landslides of waste dumps.

The phenomenon of self-heating and spontaneous combustion is a result of a number of complex physical and chemical processes. Spontaneous combustion within mine waste dumps presents a multifaceted challenge, impacting environmental safety and structural stability. Spontaneous combustion, often triggered by the oxidation of coal under favorable conditions, can lead to significant thermal and mechanical changes within the dump material. These include temperature increases, material degradation, and gas generation, all of which can also cause geological disasters such as surface landslides and explosions.

Self-heating and spontaneous combustion is being observed in many coal fields and mine waste dumps worldwide, such as in the Czech Republic [9–12], Australia [13], China [14–17], South Africa [18,19], US [19], Poland [20–24] and India [25]. It is well-known that the temperature of the environment and that within the slope affect its stability, especially when there are intense thermal fluctuations that cause changes in the volume of soils and rocks, which can lead to thermal stresses and the weakening of the slope. Additionally, an increase in temperature may cause changes in soil moisture and increase permeability, thereby reducing the shear strength of rocks and soils and their cohesion, which can contribute to landslides [26–37]. Other studies have shown how wildfires affect natural slopes and lead to landslides [38–40].

In the case of coal mine waste dumps, the impact of temperature on the slope stability is certainly also significant. On 16 September 2023, a landslide occurred in a coal mine waste dump in southern Poland, where the phenomenon of the self-heating and spontaneous combustion of coal is constantly observed. Figure 2 shows the landslide surface. One of the major causes of landslides is cracks/fractures induced by coal combustion, observed on the upper surface of the slope; this could initiate the development of slope damage and lead to a landslide. This is evidence of the potential direct impact of the spontaneous combustion of coal on slope stability within mine waste dumps.

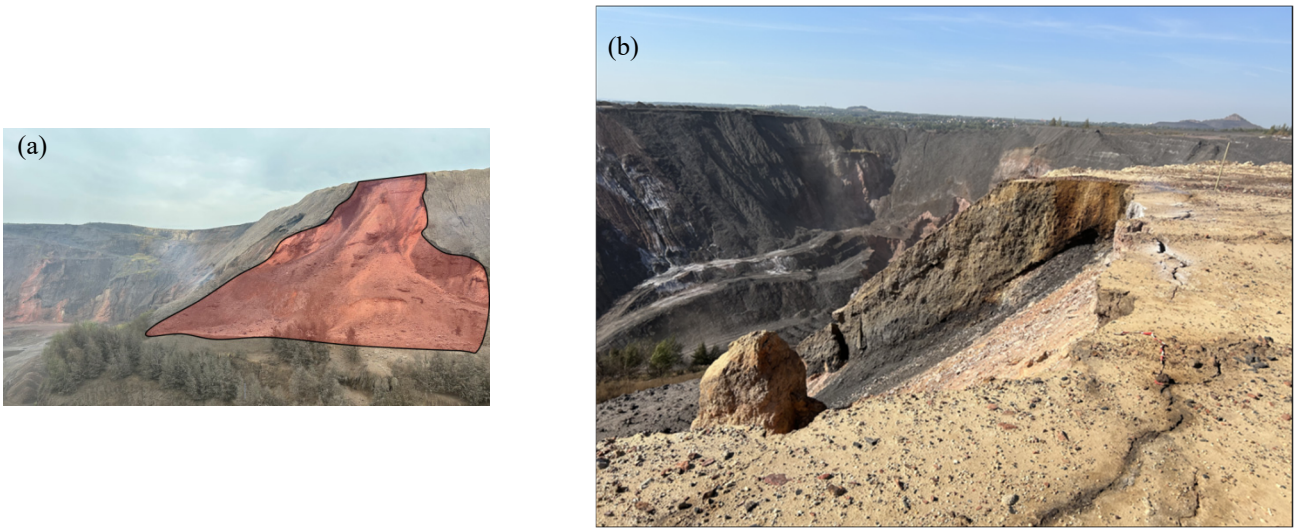


Figure 2. Slop failure at a coal mine waste dump in southern Poland: (**a**) view from the slope toe; (**b**) view from the slope crest.

Despite the potential risks, the impact of coal combustion on the slope stability of mine waste dumps remains poorly understood. This review explores the impact of self-heating and spontaneous combustion on slope stability, emphasizing the underlying mechanisms, thermal effects, material behaviour, and viable monitoring, prevention, and mitigation strategies for mine waste dumps. The review aims to provide a comprehensive analysis of current knowledge and identify areas where further research is needed. A better understanding of self-heating and spontaneous combustion in mine waste dumps can help mines assess risks and minimize impacts effectively.

2. Mechanisms of Spontaneous Combustion in Coal Mine Waste Dumps

The spontaneous combustion process typically involves four distinct phases: (1) the induction phase—heating and accumulation by oxidation (internal temperature increase); (2) slow spontaneous heating—internal temperature increase and the maintenance of a fixed temperature; (3) the acceleration of heating—the drying of internal moisture and a rapid increase in temperature; and (4) spontaneous combustion—high-temperature burning alters material properties and produces gaseous byproducts [19,41–45].

Spontaneous combustion occurs due to the self-heating of combustible materials (coal, sulfide and pyrite) contained in the wastes through low-temperature oxidation. This process is accompanied by an increased production of heat and increased temperatures (Figure 3).

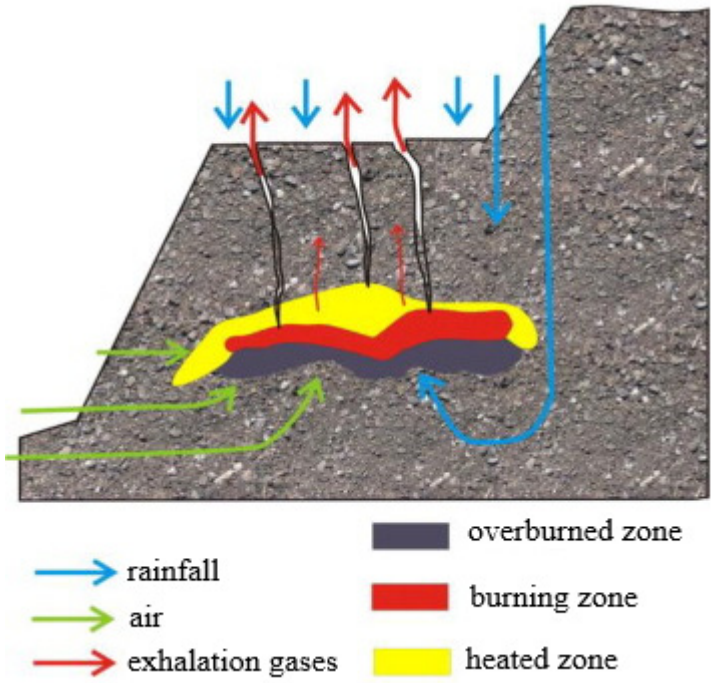


Figure 3. Schematics of spontaneous combustion within the mine waste dump [46].

Major factors influencing this process include the following:

- Coal Rank: higher-rank coals (e.g., anthracite) have lower susceptibility to spontaneous combustion than low-rank coals (e.g., lignite). Coal is a porous material characterized by a complex structure with numerous active sites on its surface. These sites can continuously adsorb oxygen molecules from the surrounding air. During this process, coal undergoes low-temperature oxidation, which results in the gradual release of gaseous products and heat. Under certain conditions—such as restricted ventilation, high ambient temperatures, and sufficient coal mass—this heat can accumulate faster than it dissipates. As a result, the temperature of the coal gradually rises, potentially reaching the critical threshold at which spontaneous combustion occurs [47–54].
- Particle Size: fine coal particles with an increased surface area are more prone to oxidation. The particle size and porosity of coal significantly influence its specific surface area. A larger specific surface area enhances the contact between coal and oxygen, thereby increasing both the reaction rate and the efficiency of heat transfer. As the particle size decreases, the likelihood of spontaneous heating increases; studies have shown that a reduction in particle size can raise this tendency by approximately 12–14% [13,52,55–60].
- Moisture Content: field observations and studies have consistently indicated that moisture condensation can enhance the potential for spontaneous combustion. Moderate moisture levels facilitate oxidation, while excessive moisture can inhibit the process [18,61–72].
- Ambient conditions: high ambient temperatures and oxygen availability accelerate self-heating [19,73–79]. Additionally, external heat sources, such as wildfires, human activities such as the removal/reconstruction of the mine waste dump or wind flow, delivering air to the self-heating cells, can initiate combustion [22,80–84].

3. Thermal Effects on Geotechnical Properties

The environmental impacts of spontaneous combustion are well-documented and include air pollution, acid rain, and greenhouse gas emissions. However, the geotechnical impacts, particularly on mine waste dumps, have received less attention. The combustion process can alter the physical, chemical and mechanical properties of coal and its associated wastes, leading to changes in slope stability. The stability of any slope is heavily influenced by the geotechnical conditions of the site including the physical and mechanical properties of the built-up materials and hydrological conditions. Coal combustion generates substantial heat, affecting slope stability through various mechanisms: thermal expansion, material degradation, and gas generation, significantly altering the geotechnical properties of mine waste materials, which are critical for slope stability. Key impacts include:

Reduction in Shear Strength: In the middle of the slope, where combustion occurs, the temperature can reach several hundred degrees Celsius [20,43,85–87]. Various research studies have pointed out the impact of the temperature of soils and rocks strength [88–100]. Temperature gradients within the dump generate thermal stresses, which can lead to material cracking. In clay-rich dump materials, these temperature variations can induce significant fractures, compromising structural integrity. Elevated temperatures accelerate the decomposition of thermally sensitive minerals, such as pyrite, leading to the release of acidic byproducts and further weakening the material. Additionally, thermal expansion contributes to material degradation, weakening the bonds between particles and reducing the shear strength of the waste material, including the cohesion and friction angle. This reduction in shear strength is a primary factor contributing to slope instability, increasing the risk of failure in waste dumps and other natural/man-made earth structures.

Thermal Stress Accumulation: Combustion within the mine waste dump generates gases that accumulate over time, leading to an increase in pore pressure and a subsequent reduction in effective stress. As the pressure builds up, these gases eventually escape through the dump, creating pathways that often manifest as surface fractures and/or cracks (Figure 4). This process induces volumetric expansion, which can weaken the structural integrity of the slope, potentially triggering progressive failure mechanisms and ultimately leading to a landslide. Additionally, the formation of an extensive fracture network further compromises slope stability by facilitating water infiltration, accelerating weathering, and reducing overall material cohesion.



Figure 4. Occurrence of cracks/fractures on the slope surface caused by coal combustion within the dump body.

An example of 2D slope stability analysis showed the significant influence of fractures orientation and length on slope stability (Table 1).

Table 1. Results of a simple slope stability analysis.

FoS		Slope Angle, °		
		23	26.6	31
Crack orientation and length	Without cracks/fractures	1.45	1.19	1.0
	6 m long, the dip angle close to the slope surface	1.18	1.04	0.98
	12 m long, the dip angle close to the slope surface	1.03	0.86	0.83
	6 m, dip angle of 90° (vertical)	1.33	1.09	1.0
	12 m, dip angle of 90° (vertical)	1.27	1.05	0.89

Many other studies have also pointed out the significant impact of discontinuities on slope stability in various regions worldwide [101–114].

Changes in Density and Compaction: The formation of voids within the mine waste dump after the combustion process is primarily due to the thermal degradation and oxidation of carbonaceous materials, leading to volume reduction and structural collapse. When self-heating or spontaneous combustion occurs within the dump, organic matter, sulfides and/or carbon, and other combustible materials undergo exothermic reactions, producing gases. As these gases escape, they create cavities within the dump. Additionally, the combustion process results in the thermal decomposition of minerals, altering their physical and mechanical properties. Clays and sulfates may dehydrate, while carbonates can decarbonate, further reducing the material volume. This progressive loss of solid mass, combined with the weakening of interparticle bonds due to high temperatures, causes differential settlement and localized collapses, leading to the development of interconnected voids and subsurface cavities (Figure 5). Over time, these voids can expand and coalesce, potentially resulting in ground instability, surface subsidence, and increased permeability within the waste dump. The extent of void formation depends on factors such as the composition of the waste material, the combustion intensity, the temperature distribution, and the presence of moisture, which influences thermal conductivity and reaction kinetics [24,72,115–118].

Increased Porosity and Permeability: Thermal fractures increase dump permeability, altering water flow patterns and promoting localized saturation. This significantly influence the stability of structures. When the slope body experiences high temperatures, thermal expansion and differential stresses generate new fractures and widen existing ones, enhancing fluid flow pathways. Additionally, the decomposition of minerals and the loss of cementing agents further contribute to the development of secondary porosity. This increased permeability enhances vertical and lateral water movement, potentially concentrating moisture in specific zones rather than allowing uniform drainage. Localized saturation can weaken dump stability by reducing matric suction in unsaturated zones, leading to strength loss and an increased susceptibility to slope failure. Additionally, the altered flow paths may accelerate the leaching of contaminants, affecting groundwater quality [87,119–125].



Figure 5. A cavity formed within a mine waste dump.

4. Monitoring and Mitigation Strategies Combating Spontaneous Combustion

4.1. Monitoring Techniques

Temperature monitoring, both on the surface and within the dump, is one of the most direct and reliable indicators of the extent of spontaneous combustion. Continuous gas monitoring also provides valuable information, as the presence and intensity of combustion can be inferred from the distinctive odor of released gases, which is often associated with hydrocarbons.

Over the past few decades, numerous studies worldwide have focused on various techniques for detecting and monitoring spontaneous combustion in mine waste dumps. One commonly used approach is **field surveying**, which includes a range of in situ observations such as waste material characteristics, ambient environmental conditions, the emission of gases with hydrocarbon-like odors, the appearance of brown discolorations on the dump surface, and signs of sulfur mineralization. However, despite its usefulness, field surveying is generally characterized by low efficiency, high costs, and significant time requirements, making it unsuitable for large-scale detection and the continuous monitoring of extensive waste dump areas [81,126–129].

The monitoring of spontaneous combustion in mine waste dumps is usually carried out through **borehole temperature and gas measurements** at different depths [3,7,43,86,130–136]. However, temperature and gas measurements over a large area are expensive and inefficient, and in some cases they are impossible due to a lack of access to places with a high intensity of spontaneous combustion due to numerous hazards (toxic gases, collapses and landslides after burning). Its reliability also often depends on the density of measuring points for the whole area under evaluation, leading to high costs and lengthy construction timelines.

Because of their high cost and time performance, field survey and borehole temperature and gas measurement techniques are commonly used to validate the results obtained from others methods [131,136–140].

Temperature measurement has been used for monitoring the spontaneous combustion of mine waste dumps by applying advanced technologies such as small-scale unmanned aerial vehicles (UAVs), large-scale satellite remote sensing, infrared imaging remote sensing and multi-source data fusion monitoring [24,137–153]. These technologies offer several advantages, including a reduced need for direct contact with the objects observed and the elimination of the risk of exposing personnel to hazardous fire zones. Equipped with high-precision sensors, aerial platforms can remotely detect the position, status, and other relevant data of target objects with a high degree of accuracy. However, these approaches usually require knowledge of the intensity and range of the fires. Consequently, these methods are not well-suited to detecting the potential spontaneous combustion process in its initial stages when the spontaneous combustion has not occurred yet on the surface and/or shallow subsurface of the dump, i.e., the combustion cells are located deep within the dumps. In such cases, combustion cells may be located deep within the dump body, making early detection difficult with surface-based thermal imaging techniques.

Another alternative approach is based on **monitoring vegetation changes**, which are considered to be signals of underground temperature rise. It is well-known that spontaneous combustion releases a constant heat, which creates a stress environment for vegetation growth. Under the influence of an abnormal surface/underground temperature, vegetation is likely to decrease [154–158]. A number of studies have carried out investigations on reclaimed coal waste dumps by using a UAV equipped with an aboveground biomass (AGB) camera [144,159–162]. This approach is also not suitable for detecting the potential spontaneous combustion process in its initial stages and cases where the combustion cells are located deep within the dumps. It also can be noted that active mine waste dumps are not covered by vegetation, so this method can only be applied for the claimed mine waste dumps.

Despite the frequent occurrence of spontaneous combustion events in mine waste dumps worldwide, there remains a lack of effective early warning and monitoring methods for assessing the potential risk. Although some progress has been made in developing ensemble or hybrid techniques that integrate multiple detection and monitoring approaches, these methods are still in the early stages of development. Such combined techniques hold considerable potential to enhance robustness and accuracy by leveraging the strengths of individual methods while compensating for their respective limitations. However, substantial research and development efforts are still required to advance these combined systems and validate their performance under real-world conditions. In conclusion, while significant advancements have been made in the detection and monitoring of endogenous fires, several challenges remain. These include the site-specific applicability of many techniques, the limitations of laboratory studies, and the early development of combined approaches. These issues underscore the need for continued research aimed at improving the accuracy, generalizability, and practical applicability of spontaneous combustion monitoring across a wide range of environmental and operational contexts. For example, integrating thermal infrared imaging with gas/temperature detection sensors may significantly enhance the reliability of monitoring systems under variable environmental conditions.

4.2. Mitigation Strategies

Any combustion can be controlled by removing any one of the three essential components: fuel, heat and oxygen. In order to extinguish a fire, it is necessary to remove at least one of these components.

Based on experience with spontaneous combustion in South Africa, the control measures can be divided into three groups: (1) control measures to reduce or eliminate oxygen from the fire process, including sealing agents, dozing over, buffer blasting, and the cladding of the highwall; (2) control measures to reduce the temperature (heat) and/or the reaction rate, including the injection of water, nitrogen, and carbon dioxide; and (3) the removal of heated or burning material for cooling the combustion sites and interrupting the reaction [163–166].

Throughout the history of coal mining in Poland, a variety of methods have been employed to extinguish burning mine waste dumps or prevent their spontaneous combustion [1,20,81,167,168]. These measures include intensive sprinkling with water, covering dumps with nonflammable materials such as clays or tills, the isolation of parts of the dump that are on fire by digging absorption trenches filled with a water–ash mixture, the cooling of burning waste via its exploitation and the reconstruction of dumps, deep drilling into the dump to enable the filling of openings with water–ash pulp, cooling and quenching with neutral gases using pipes placed in the dump during its deposition, waste thickening with an incombustible material combined with dump dehydration in order to protect the dump from self-ignition and protect groundwater from chemical compounds leached from the deposited waste, covering the dump with polymeric compounds or antipyrogenic materials (sodium chloride, calcium chloride or manganese chloride), and utilizing ash from power plants during dump formation.

At Australian mine sites, a number of control techniques have been incorporated into waste rock dump (WRD) design and mine planning to minimize the effects of spontaneous combustion and ultimately prevent it from occurring. These control measures are quite similar to those employed in South Africa and can be broadly categorized into three groups: measures to reduce/eliminate oxygen, such as sealing agents, the compaction of the surface material (dozing over, truck haulage routes or compaction), buffer blasting, covering the area of concern with inert material (e.g., non-acid forming material, clay), the application of a final cover layer with good water retention properties (e.g., fly ash-water slurry) and subaqueous deposition; measures used to reduce the temperature and lower the reaction rate, including water cannons, firefighting foam, the injection of water, water spraying, nitrogen injection and carbon dioxide injection; measures to eliminate the fire process, which may include the excavation of hot or burning material, controlling the morphology of potentially acid-forming material cells (layering, etc.), the use of low-angle slopes to minimize the effects of wind (i.e., reduce "chimney effect"), the use of artificial wind barriers, submersion in water (e.g., backfill in pit and flooding), and the spreading of the affected material into thin piles to allow it to cool [13,64,133,169,170].

Techniques or approaches that have been proposed and applied in the US, India and other countries include bulkheads and stoppings; inertization; nitrogen or carbon dioxide gas injection; dynamic pressure balancing, ventilation control; the application of fire-fighting chemicals; the application of a surface coating or sealant material to prevent oxidation; high-expansion foam; excavation; isolation; inundation with water; surface seals; remote sealing; noncombustible barriers; hydraulic backfilling or 'flushing'; pneumatic stowing; and grouting [17,171–179].

Alternative approaches are focused on the development of advanced materials that can be effectively used to combat combustion. These include multi-phase foams, hydrogel mixtures, and foamed gels; these materials offer potential for fire suppression across various environments. Multi-phase foam and hydrogel mixtures combine the thermal insulation properties of foams with the high water content and cooling capacity of hydrogels, resulting in enhanced fire resistance and heat absorption capabilities. Foamed gels, produced by incorporating gas bubbles into gel matrices, provide prolonged surface adherence

and function as both a physical barrier and a heat sink. Another innovative strategy involves integrating foam into traditional grouting materials, thereby improving their fire-suppressive performance while maintaining structural integrity [180–186]. These materials demonstrate superior cooling and smothering capabilities compared to water or conventional combustion retardants—especially in high-temperature or oxygen-deficient environments. However, they also have limitations. Their production and application tend to be more costly, and they may present environmental and health concerns if not properly managed. Additionally, these materials often require specialized equipment for application, and their long-term effectiveness can be compromised by factors such as evaporation, chemical degradation, or exposure to environmental conditions.

5. Discussion

This chapter is dedicated to a comprehensive evaluation of the current state of knowledge and the development and implementation of designs able to address spontaneous combustion hazards, as well as their possible impact on slope stability. It provides an in-depth analysis of existing strategies, assessing their effectiveness in preventing and mitigating the risks associated with spontaneous combustion in mine waste dumps. The chapter also explores the challenges and limitations faced in research and practical application. In addition to evaluating current approaches, key research gaps have been identified, particularly in the areas where innovative advancements are needed. To address these issues, future research directions are proposed. The goal is to refine existing methods and introduce more sustainable, cost-effective solutions for combating spontaneous combustion, ensuring enhanced safety and environmental protection in mine waste dump operations.

Integrated Modelling Research: Numerous studies have been conducted on spontaneous combustion in mine waste dumps, each addressing different aspects of this complex phenomenon. Much research has focused on the thermal behavior of the waste material, investigating oxidation processes, heat generation rates, and temperature distribution within the dump [5,6,41–45]. Other studies have examined the environmental impacts, such as greenhouse gas emissions, air pollution, and the release of toxic substances [7,16,22,24,32,34,37,43]. Additionally, a number of research studies have been conducted on the physical and chemical properties of mine waste, including its moisture content, particle size distribution, and coal/sulfide content, which influence the likelihood and progression of combustion [9–12,17,19,47–72]. There is also a body of work exploring the mechanical behavior of waste dump slopes, particularly in terms of slope stability, settlement, and deformation [42,88–125]. However, there remains a critical gap in the literature when it comes to studies that integrate thermal and mechanical aspects—that is, research that explicitly investigates how thermal processes (such as combustion and heat transfer) affect the mechanical response of mine waste dumps, including strength reduction, creep, and failure mechanisms. Most existing studies tend to treat thermal and mechanical phenomena in isolation, failing to capture the coupled interactions that are essential for understanding the realistic behavior of mine waste structures subjected to elevated temperatures. To address this limitation, there is an urgent need for the development of integrated thermo-mechanical models that can simulate the complex interplay between heat generation, thermal expansion, material degradation, and mechanical deformation. These models should incorporate multi-physics processes, including heat generation and transfer due to the oxidation of residual coal; gas flow and pressure build-up within the pore structure; thermal-induced softening and changes in shear strength; time-dependent deformation (creep) under sustained thermal and mechanical loads; and failure prediction under varying boundary and environmental conditions. Such integrated modeling frameworks are essential tools for advancing our predictive capabilities. By combining

laboratory testing, field monitoring, and numerical simulations, we can better understand how spontaneous combustion evolves and impacts dump stability over time. These models would not only support proactive risk assessment and early warning systems but also inform the design of more resilient waste dump structures and targeted mitigation strategies, such as thermal barriers, compaction methods, and improved dump geometry. A coupled thermo-mechanical modeling to bridge the gap between existing studies and real-world conditions is needed for accurate predictions. This integrated approach is crucial for managing the long-term safety and environmental risks associated with mine waste dumps prone to spontaneous combustion.

Long-Term Material Behavior: A number of research studies have been conducted to gain a better understanding of the mechanisms underlying spontaneous combustion. While the impact of spontaneous combustion on slope stability is critical, there remains a significant lack of geotechnical investigations at many affected sites. This gap in the research may be attributed to the heterogeneous nature of materials comprising mine waste dumps, as well as the substantial costs and logistical challenges associated with conducting such studies. Moreover, there is currently no comprehensive research focusing on the post-combustion residual strength and creep behavior of materials within mine waste dumps. This is a crucial oversight, as these properties are essential for evaluating long-term slope stability and the risk of delayed failures following combustion events. It appears that mine waste dumps are often not given sufficient attention in terms of geotechnical assessment until spontaneous combustion or spontaneous combustion-induced consequences have already occurred. To address this issue proactively, it is imperative to conduct long-term experimental research into the behavior of mine waste materials under elevated thermal conditions. Such studies should aim to characterize changes in the mechanical properties, deformation behavior, and overall structural integrity over time, thereby enabling the more effective prediction, prevention, and mitigation of spontaneous combustion hazards.

Sustainability: A number of methods have been developed and applied worldwide over the years. The effectiveness of these techniques is dependent on individual site situations. Fuel is removed when it is physically separated from the burning mass; therefore, in surface subjects such as spoil piles or mine waste dumps, the removal of carbonaceous or sulfide minerals is normally unrealistic. The removal of heat can be accomplished by injecting a heat-absorbing material; i.e., water, inert gas, foam, grout, etc.; however, it is usually impractical. Additionally, these materials can have effects on the environment surrounding dumps, such as the air, surface/underground water, noise, vegetation and eco-system. Hence, most strategies for the control and prevention of spontaneous combustion focus on removing oxygen, or rather, preventing it from accessing the fuel. This is usually best accomplished by applying cover layers of inert material, which reduce the rate at which oxygen can penetrate the mine waste dump. The effectiveness of a cover is generally dependent on the composition, particle size and bulk density, water content of the cover, air-filled void space, heat transfer capacity, oxygen transfer, and cover thickness. However, the cover layer can make the slope instable because it adds mass to the slope. The excavation of heated or burning material is one of the primary methods used to control spontaneous combustion in mine waste dumps. The effectiveness of this approach depends on several factors, including the layout of the waste dump, the extent of the combustion problem, and site-specific conditions. When implemented properly, this method results in the complete elimination of burning zones and facilitates the relatively rapid cooling of adjacent areas, typically within a few hours to several days. However, despite its effectiveness, excavation has several drawbacks. The process generates significant amounts of dust, which can have adverse environmental and health impacts, leading to complaints from nearby communities. Moreover, excavation alters the shape and size of the dump,

necessitating design and operational modifications to maintain stability and ensure continued waste disposal efficiency. In the case of active dumping sites, excavation operations can also disrupt the continuity of waste disposal activities, requiring careful planning and coordination to minimize operational downtime. Additionally, handling and relocating burning or heated materials pose safety risks to workers and require appropriate protective measures. Given these challenges, excavation should be carefully planned in conjunction with other fire mitigation strategies, such as controlled compaction, surface sealing, and the continuous monitoring of temperature and gas emissions, to ensure a comprehensive and sustainable approach to spontaneous combustion management. Practically, there is no single control measure that has been proven to be completely reliable or successful. The effective control of spontaneous combustion is usually achieved by using a combination of techniques. Hence, developing eco-friendly mitigation techniques is critical for the long-term management of spontaneous combustion in mine waste dumps.

Climate Change: Self-heating in mine waste dumps is strongly influenced by ambient conditions such as temperature, wind, rainfall (including snowfall), and atmospheric pressure. These environmental factors play an important role in the onset of spontaneous combustion. The increasing frequency and intensity of extreme weather events due to climate change can exacerbate the risk of spontaneous combustion in mine waste dumps. Rising temperatures, prolonged dry periods, intense rainfall, and unpredictable weather events can all alter the moisture content, air circulation, and temperature gradients within the dump. This can accelerate self-heating processes, leading to an increased risk of combustion and further impacting the stability of the dump slope. In the context of climate change, these effects are likely to become more pronounced, necessitating adaptive management strategies for the safe handling and monitoring of mine waste dumps. Currently, the effects of extreme weather events due to climate change on combustion remain understudied.

Alternative approach on mine waste dump management: Energy from the combustion process can be used as a continuous geothermal heat source. The combustion process releases greenhouse gases, contributing to air pollution, acid rain, and climate change. Additionally, it produces particulate matter and toxic heavy metals, which can degrade air quality and pose health risks. From a geotechnical perspective, spontaneous combustion within mine waste dumps can lead to thermal fractures, increased permeability, ground subsidence, and structural instability. The heat generated alters the physical and chemical properties of surrounding materials, potentially weakening the dump structure and influencing water flow patterns. Despite a number of negative impacts, spontaneous combustion is a significant source of energy. Controlled combustion can remain an essential energy source for district heating systems or industrial applications, where its steady heat output is harnessed for efficient thermal energy production. Similar concepts have been explored in municipal solid waste landfills to optimize energy recovery [187–198]. Moreover, although various technologies have been tested and implemented to mitigate spontaneous combustion in mine waste dumps, long-term success remains elusive. Frequent spontaneous combustion events continue to be observed in mine waste dumps worldwide, highlighting the persistent challenge of controlling these events. Given the high cost and uncertain effectiveness of traditional hazard mitigation strategies, a shift in perspective may be necessary. Instead of solely focusing on extinguishing and eliminating spontaneous combustion-induced hazards, a more pragmatic approach could involve hazard awareness, risk control, and the strategic utilization of the generated heat. Maximizing the energy potential of controlled combustion could provide tangible benefits to surrounding communities, turning an environmental and safety challenge into a potential energy resource. Figure 6 presents the concept of utilizing energy from the combustion process.

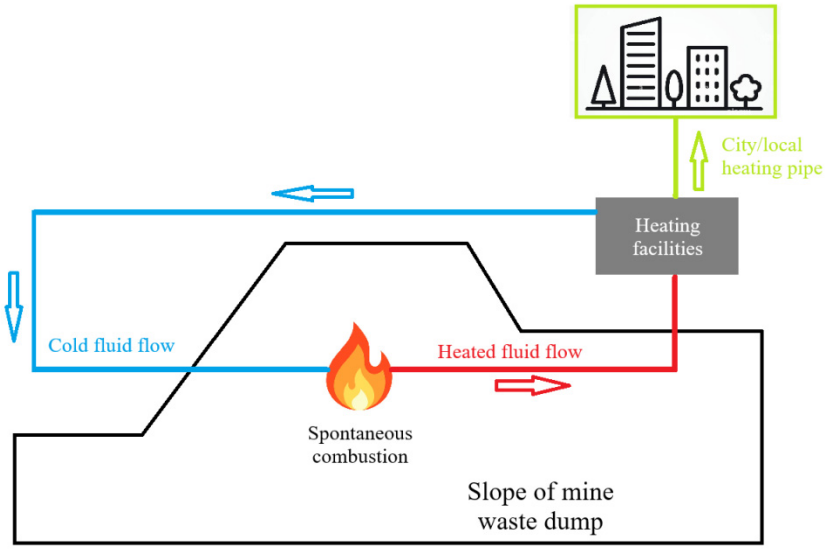


Figure 6. A simplified concept of the city/local heating system configuration in a mine waste dump.

6. Conclusions

Due to the fact that mining plays a crucial role in the economy and national security of many regions worldwide, the quantity and size of mine waste dumps are expected to increase over time. As these dumps grow in volume and dimensions, the likelihood of self-heating and spontaneous combustion events also rises—particularly in mining areas. Spontaneous combustion alters the thermal conditions within the waste material, which directly influences the geomechanical behavior of the dump materials. These thermally induced geomechanical changes can, in turn, impact the overall stability of the waste dump slopes. In other words, spontaneous combustion within mine waste dumps introduces complex challenges related to slope stability, posing significant risks to both environmental safety and operational sustainability.

Due to the variability of geotechnical properties, the spread of combustion within the mine waste dump and the ongoing process of waste deposition should be subject to continuous detailed monitoring. Such a monitoring should cover changes in dump slope geometry; the degree of compaction of individual layers forming the dump body; slope displacements resulting from geometric changes during its dumping operations; the type and grain size of freshly deposited mine waste; ongoing slope stability analyses and calculations for each phase of slope construction; and thermal imaging surveys and in-depth thermal state investigations during the dumping process. The primary objective of this monitoring is the early warning and prevention of potential spontaneous combustion and its possible consequences. This approach is also essential for the selection and assessment of fire prevention methods, both during the construction phase of the reclamation body and the post-construction phase, ensuring the long-term safety and performance of the dump structure.

A number of practical measures are recommended to maintain the stability of mine waste dump slopes. These include conducting stability analyses for individual mine waste slopes and continuous monitoring such as geodetic and photogrammetric measurements to track slope displacements over time. Additionally, geophysical investigations should be carried out to detect potential voids within the dump body. The most commonly used geophysical methods include ground-penetrating radar, engineering seismics, electrical resistivity tomography, gravimetric methods, and electromagnetic methods. These investigations are a crucial complement to geotechnical studies, especially in terms of accurately identifying the structure and geomechanical condition of the dump materials. It is also

recommended that the compaction of freshly deposited mining waste is monitored and, if necessary, that the surface layers of the dump body are re-compacted or sealed to achieve the required compaction indicators for each material (soil) layer.

Preventive measures to mitigate spontaneous combustion at mine waste dumps have traditionally been costly, time-consuming and labor-intensive. Until now, despite these efforts, they have not proven fully effective in eliminating or sustainably controlling the issue. Therefore, eco-friendly mitigation techniques should be developed for the long-term management of mine waste dumps affected by spontaneous combustion. An alternative approach worth considering is controlling and utilizing spontaneous combustion as a geothermal heat source. This concept could transform a hazardous phenomenon into a beneficial resource. Future work should focus on the design, feasibility, and development of such a system, as well as its implementation. Investigating this approach may offer a sustainable and innovative solution for managing mine waste dumps prone to spontaneous combustion.

Future research should focus on thermal–mechanical interaction, long-term monitoring, advanced analytical techniques, numerical modelling, innovative mitigation strategies and sustainable mining practices to enhance the management of spontaneous combustion itself and its possible impact on the slope stability of mine waste dumps.

Future research on the impact of climate change on self-heating and spontaneous combustion in mine waste dumps can focus on several key areas to improve understanding and mitigation strategies: it could investigate how changes in extreme weather events (e.g., heatwaves, intense rainfall, and droughts) influence self-heating and the onset of spontaneous combustion in mine waste dumps; develop advanced predictive models that incorporate climate change projections to assess the future risk of spontaneous combustion in waste dumps; enhance real-time monitoring techniques to detect early signs of spontaneous combustion and self-heating in the context of changing climate conditions; and investigate adaptive management strategies for mine waste dumps that take into account future climate scenarios.

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