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Review of the civil use of explosives and the impact of post-blast gases on the environment
Przegląd zużycia materiałów wybuchowych do użytku cywilnego oraz oddziaływania gazów postrzałowych na środowisko

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Abstract: *Explosives play a fundamental role in mining, enabling efficient rock fragmentation and supporting the increasing demand for mineral resources. In recent years, the focus of explosives engineering has gradually shifted from achieving maximum detonation performance toward reducing environmental impact and improving sustainability. This paper provides an overview of explosives consumption from the global, European, and Polish perspectives, with particular attention to current technological trends and environmental aspects of blasting operations. The review highlights the growing use of bulk emulsion explosives, such as ANFO, which are gradually replacing conventional explosives, due to their improved safety and lower emission potential. Special attention is given to the formation of post-blast gases, especially carbon monoxide and nitrogen oxides, as well as methods used to monitor their presence and limit their impact. Environmental and health considerations are discussed alongside a comparison of legal regulations in Poland and selected European Union countries, indicating the need for more precise and more consistent toxicity standards.*

Streszczenie: *Materiały wybuchowe odgrywają kluczową rolę w przemyśle górniczym, umożliwiając efektywne urabianie skał oraz wspierając rosnące zapotrzebowanie na surowce mineralne. W ostatnich latach obserwuje się jednak zmianę podejścia w inżynierii materiałów wybuchowych z maksymalizacji parametrów detonacyjnych w kierunku ograniczania oddziaływania na środowisko oraz zwiększania zrównoważonego charakteru procesów wydobywczych. W artykule przedstawiono przegląd zużycia materiałów wybuchowych w ujęciu globalnym, europejskim oraz krajowym, ze szczególnym uwzględnieniem aktualnych trendów technologicznych i środowiskowych aspektów prowadzenia robót strzałowych. W opracowaniu zwrócono uwagę na rosnące znaczenie* *materiałów wybuchowych emulsyjnych luzem, które stopniowo zastępują konwencjonalne materiały wybuchowe, takie jak ANFO, ze względu na wyższy poziom bezpieczeństwa oraz niższy potencjał emisyjny. Szczególną uwagę poświęcono wytwarzaniu gazów postrzałowych, w szczególności tlenku węgla oraz tlenków azotu, a także metodom ich monitorowania i ograniczania ich oddziaływania. Omówiono również aspekty środowiskowe i zdrowotne w kontekście porównania regulacji prawnych obowiązujących w Polsce oraz w wybranych krajach Unii Europejskiej, wskazując na potrzebę wprowadzenia bardziej precyzyjnych i spójnych standardów toksyczności.*

Keywords: *explosives, post-blast gases, legal regulations, safety*
Słowa kluczowe: *materiały wybuchowe, gazy postrzałowe, przepisy prawne, bezpieczeństwo*

1. Introduction

Explosives play a key role in the mining industry, enabling efficient rock fragmentation and extraction of mineral resources on the scale required by today’s economy. The continuous development of global infrastructure, energy transformation processes and the growing demand for critical raw materials have strengthened the link between economic development and the intensity of blasting operations. Market analysis indicates that the mining sector remains a major consumer of industrial explosives, while the growing use of precision blasting technologies in the form of electronic detonators, reflects the need to improve efficiency and reduce unnecessary energy losses during rock fragmentation [1, 2]. In Poland, explosives remain an important element of mining operations in the extraction of coal, metal ores and aggregates. Their use is closely related to the scale of production, geologic conditions and safety requirements. Reports of the State Mining Authority and the Central Mining Institute – National Research Institute (GIG-PIB) confirm that blasting operations are still one of the key processes determining both productivity and safety of operations in mining environments [3, 4]. For many years, the development of explosives has focused mainly on improving energetic parameters, including detonation velocity, pressure and overall fragmentation efficiency. In recent years, however, the priorities of explosives engineering have gradually evolved. In addition to the effectiveness of blasting operations, increasing attention is now being paid to safety, environmental impact, emission reduction and sustainability throughout the entire life cycle of explosives.

Studies show that the composition of the explosive, blast design and operational conditions have a significant influence on the formation of toxic post-blast gases, especially carbon monoxide (CO) and nitrogen oxides (NO_x) [5, 6]. At the same time, advances in the field of emulsion explosives and modified formulations have allowed for the reduction of incomplete detonation and the reduction of toxic emissions compared to conventional explosives such as ANFO and dynamites, where incomplete detonation refers to a condition in which the explosive reaction does not fully propagate through the explosive charge, resulting in only partial energy release thereby potentially leaving unreacted material [7, 8]. This change reflects wider European efforts to reduce the environmental footprint of the mining industry and improve air quality standards [9]. Current research and industrial practice increasingly focuses on reducing emissions while maintaining or improving blasting efficiency. Therefore, the concept of green explosives has emerged, which includes the development of optimized bulk emulsion formulations, the use of catalytic additives to limit NO_x formation and the gradual elimination of environmentally harmful components, such as TNT from explosive boosters [10, 11]. At the same time, digital tools and decision-support systems, ranging from specialized blast pattern design software to unmanned aerial vehicles for 3D scanning of the mining faces, are becoming more widely used. These systems, often powered by artificial intelligence, allow for better control of energy distribution, reduction of overbreak and lower emissions of gases and dust [12, 13]. Combined with advances in gas monitoring and ventilation optimization [14], these developments indicate a clear direction for the future of blasting operations, where efficiency, safety, and environmental responsibility are increasingly treated as equally important objectives.

The main objective of this paper is to provide a comprehensive overview of explosive consumption and the environmental impact of post-blast gases in the context of current technological and regulatory challenges. The aim of the study is to answer three key questions: how explosive consumption in Poland has changed in relation to global and European trends, which factors determine the toxicity of post-blast gases, and what gaps exist in the Polish regulatory framework compared with selected European Union standards. The first part of the paper discusses global and regional trends in explosives consumption. The mechanisms of post-blast gas formation and monitoring methods are then analyzed and the impact on the environment and health is evaluated. The final section compares existing legal regulations and discusses future directions for the development of blasting technologies.

2. Explosives consumption

2.1. Global market

The use of explosives in mining is closely related to global economic development, infrastructure expansion and the growing demand for mineral resources required for industrial production and energy transformation technologies. The global mining explosives market has shown steady growth over the last decade, driven primarily by increased mining activity, urbanization and large-scale infrastructure investments. Global consumption of industrial explosives exceeds 15 million tons annually, with mining representing the dominant application sector. Market analyses indicate that the global value of the mining explosives sector is expected to reach approximately USD 24 billion in the coming decade, reflecting sustained expansion supported by technological development and rising demand for metals and construction materials.

A key feature of the current market dynamics is the dominant role of the Asia-Pacific region, which accounts for the largest share of global consumption. This results primarily from rapid industrialization and urbanization in countries such as China and India, where infrastructure development, urban expansion and energy-related investments significantly increase demand for raw materials and, consequently, blasting operations [15]. The development observed in open-pit mining in these regions further increases the demand for bulk explosives, mainly ANFO and emulsion-based products, due to their cost-effectiveness and suitability for large-scale operations. At the same time, global trends indicate a gradual transition toward precision blasting and digitally supported initiation systems, such as electronic detonators providing precise timing control, which are aimed to improve energy utilization, fragmentation and environmental impact. Industry reports highlight that technological innovation, including automation and digitization of blasting processes, are becoming a key factor in shaping future explosive consumption patterns worldwide [16].

2.2. Trends in the European countries

Unlike the rapidly growing markets in Asia, the European explosives market is characterized by relatively stable consumption levels, influenced by mature mining sectors, environmental constraints and regulatory pressure. A significant factor influencing the consumption of explosives in Europe was the reduction in hard coal mining. Total consumption of industrial explosives exceeded approximately 1.9 million tons in 2023, with mining and quarrying representing the dominant end-use sectors. Eastern European countries account for a significant share of consumption due to intensive mineral extraction, while Western Europe shows higher demand related to infrastructure and tunneling projects. Market forecasts indicate moderate growth, with total consumption expected to reach approximately 2.3 million tons by 2035.

Data and discussions within the European Federation of Explosives Engineers (EFEE) indicate a clear technological shift toward electronic detonators and digitally controlled initiation systems. These solutions increase blasting precision, reduce vibration and overbreak and contribute to better control of emissions and overall operational efficiency. At the same time, high energy prices in Europe have significantly impacted the production costs of ammonium nitrate, a key raw material used in many industrial explosives, leading to changes in supply chains and increased interest in alternative formulations.

European policy increasingly emphasizes environmental protection, occupational safety and the reduction of hazardous substances in industrial processes. Regulations such as the Restriction of Hazardous Substances (RoHS) directive aim to restrict the use of heavy metals and other harmful components in industrial products, which indirectly affect the design and composition of blasting accessories and initiation systems [17]. A particularly critical development in this context is the ongoing work to eliminate lead from detonator components. While environmentally justified, this transition introduces technological and logistical challenges for manufacturers and suppliers, influencing both product design and availability in the European market. Furthermore, determining and constant monitoring of the carbon footprint of explosives manufacture is becoming a major factor in competitiveness across the European market. As a result, the European explosives sector is still being shaped by the need to balance technological progress with regulatory compliance and environmental responsibility, rather than by rapid growth in overall consumption.

2.3. Polish mining

The structure of explosive consumption in Poland reflects the technological diversity of the domestic mining industry, in which both underground and open-pit operations play an important role. The scale and characteristics of the use of an explosive depend strongly on geologic conditions, mining methods and safety requirements applicable in individual sectors. Data published in annual reports of the State Mining Authority indicate that blasting remains a key method of rock excavation, both in underground metal as well as in open cast mining of aggregates and industrial minerals. In underground mining, copper mines belonging to KGHM Polska Miedź S.A. remain the largest consumers of explosives, far exceeding the consumption levels in hard coal mines. Annual consumption of explosives in copper ore mining is estimated at approximately 19-21 thousand tonnes, which significantly exceeds that observed in underground coal mining, where annual consumption is currently estimated at approximately 700 tonnes. This difference is primarily due to the adopted method of mining, geometry of deposit, scale of mining and the mechanical properties of the rock mass. Copper ore mining in Poland is conducted using the room-and-pillar mining method and dominated by drilling and blasting, mostly using bulk emulsion explosives. In open-pit mining, the total annual consumption of explosives reached almost 26 thousand tonnes, which exceeds 50% of the total consumption of explosives in mining with a clear shift towards the use of bulk emulsion explosives, as shown in Figure 1. In turn, Figure 2 illustrates the percentage share of emulsion explosives and ANFO to the overall consumption in both underground and open-pit mining.

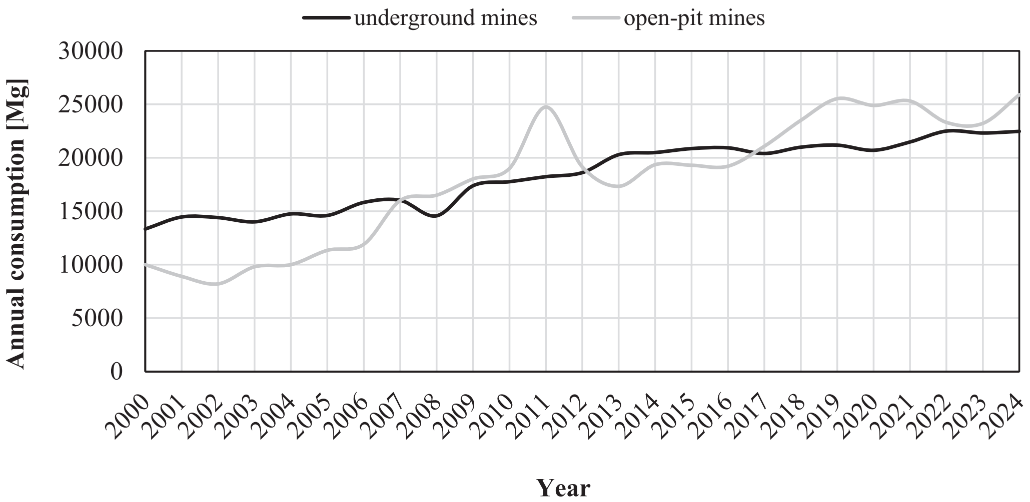

Figure 1. The total consumption of explosives in Poland between 2000 and 2024 [18-21]

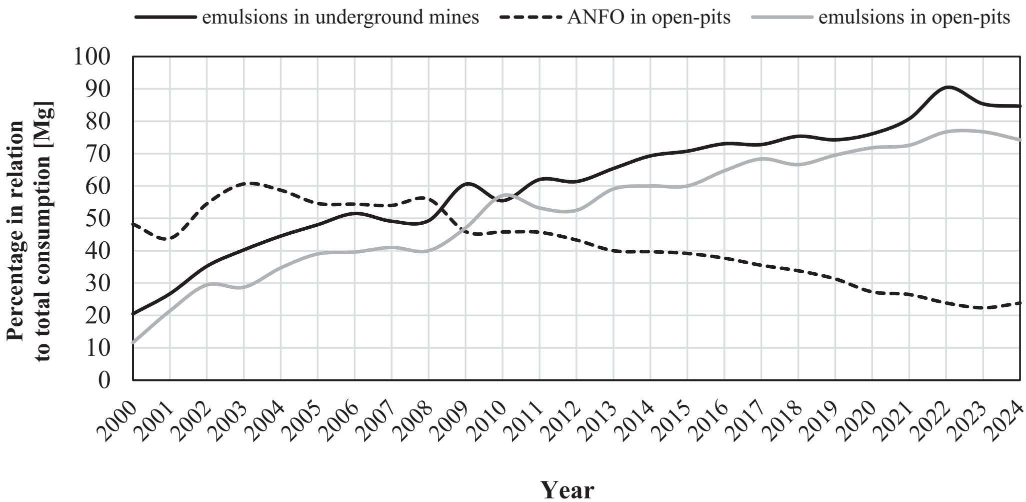

Figure 2. The proportional contribution of emulsion explosives and ANFO in Poland to the overall consumption in underground and open-pit mining between 2020 and 2024 [18-21]

From Figure 2, one may conclude that a clear and gradual technological change in blasting practices over the considered period is observed. In opencast mining, the use of ANFO has declined significantly from around 60% in 2000 to around 25% in 2024, while bulk emulsions have become dominant, with their share increasing from around 10% to almost 75%. This change was driven by several factors, including improved safety properties, higher water resistance and greater operational flexibility compared to conventional ANFO-based products. The largest increase in mineral aggregate production took place after 2005 and was closely related to the rapid expansion of road infrastructure. The demand for aggregates has increased significantly due to the development of housing and infrastructure construction, mainly the construction of roads and highways, as well as Poland's accession to the European Union. Production reached its highest level in 2011 and in the following years stabilized at around 250 million tons per year. The gradual reduction of ANFO use is mainly due to economic and operational reasons. Increasing variability of deposits conditions, including the presence of water in boreholes, reduces its performance and increases the risk of incomplete detonation, leading operators to favour emulsions which provide more stable energetic performance under variable conditions. In addition, modern mobile bulk emulsion delivery systems allow on-site manufacturing of explosives, improving logistics and reducing the risk associated with storage.

A similar but even more pronounced change is observed in underground mining, where the share of emulsion explosives increased from about 20% to around 85%. At the same time, the use of dynamites in underground mines declined significantly, from about 60% to about 15%. Overall, these changes reflect the steady replacement of former explosives with more modern and operationally advantageous technologies.

According to the latest data from the State Mining Authority, in 2023 and 2024 there were approximately 7,400 mining operations in Poland, including underground mines, open-pits and quarries with the total annual consumption amounting to nearly 50 thousand tonnes. Statistical data confirms that while the overall number of mining operations remains relatively stable, technological modernization and increasing environmental and safety requirements continue to influence the structure of explosive consumption. Overall, the Polish blasting sector demonstrates a gradual transition towards safer and more environmentally optimized explosive technologies, mainly in opencast mining, while underground operations remain highly shaped by geologic conditions and safety constraints specific to mining at great depths. Comparison of explosive consumption in global, European and Polish mining is shown in Table 1.

Table 1. Comparison of explosive consumption in global, European and Polish mining [1, 2, 22]

Parameter	World	Europe	Poland
Estimated annual explosive consumption	~15 million tons	~1.9 million tons	~0.05 million tons
Dominant application sector	surface mining	quarrying, metal mining, infrastructure	underground copper ore mining, quarrying
Main type of explosive	ANFO, bulk emulsions	ANFO, emulsions, packaged explosives	bulk emulsions
Market dynamics	moderate growth driven by raw materials demand	stable consumption, technological changes	stable consumption, structural shift toward emulsions
Key regional drivers	Asia-Pacific urbanization, infrastructure growth	environmental regulation, energy costs	geologic conditions, mining structure
Technological trends	precision blasting, digital initiation systems	electronic detonators, automation	bulk delivery systems, automation
Environmental pressure	increasing globally	high-environmental directives of EU	high-environmental directives of EU

3. Post-blast gases

3.1. Mechanisms of CO and NO_x formation during detonation

The detonation of industrial explosives is accompanied by the formation of gaseous reaction products, the composition of which depends both on the chemical formulation of the explosive and the conditions under which the detonation occurs. Among the gases produced during blasting operations, carbon monoxide and nitrogen oxides are considered the most important from the point of view of occupational safety and the environment (Table 2). Their formation is primarily related to incomplete oxidation processes occurring during detonation and in the post-detonation phase. Under ideal conditions, ammonium-nitrate-based explosives undergo reaction leading to produce mainly nitrogen, carbon dioxide and water vapour. However, deviations from stoichiometric balance or unfavourable detonation conditions result in incomplete combustion and the formation of CO. Unfavourable detonation conditions, such as charge diameter close to the critical diameter, water presence in the blast hole, mainly for non water-resistant explosives, or a lack of proper stemming, disrupt the stability of the detonation process. Furthermore, insufficient initiation energy, excessive explosive density or axial initiation along the entire charge length using detonating cord can lead to incomplete chemical transformation. These factors significantly increase the emission of toxic post-blast gases and – in extreme cases – may even lead to deflagration of the explosive. At the same time, reactions taking place at high temperatures between nitrogen and oxygen promote the formation of nitrogen oxides, especially NO and NO_2. Experimental and modelling studies show that the blast design itself, including burden, spacing and the geometry of the stopping zone, significantly influence gas generation, with the primary fragmentation zone accounting for up to 35-38% of total emissions [5].

Table 2. Typical emission ranges of CO and NO_x for selected explosives [6, 22, 23]

Explosive type	CO [dm^3/kg]	NO_x [dm^3/kg]	Relative toxicity level	Main influencing factors
ANFO (dry)	15-22	2-10	high	moisture content, oxygen balance, confinement conditions
Bulk emulsion explosives	8-15	1-4	low	sensitization method, density control, detonation stability
Dynamite	4-10	2-5	medium	nitroesters content, reaction temperature
Permissible explosives	10-30	1-4	low	reduced flame temperature, methane safety requirements

Environmental and operational factors further modify emission characteristics. Moisture content plays a particularly important role in ANFO-based explosives, where water absorption by the porous ammonium nitrate reduces the reaction efficiency and increases the volume of toxic fumes [7]. Rock type and confinement conditions influence the detonation pressure and completeness of the reaction, while blast-hole diameter and charge distribution affect the rate at which the gas expands and mixes with the surrounding air. The specific "orange smoke" visible after detonation is primarily related to elevated nitrogen dioxide (NO_2) concentrations, which are formed under oxygen-rich conditions or during the secondary oxidation of nitric oxide in the presence of atmospheric oxygen.

3.2. Measurement methods and monitoring in operational conditions

Monitoring of post-blast gases is an important element of occupational safety management in both underground and surface mining operations. Measurement techniques have evolved from simple point-based gas detection towards integrated monitoring systems capable of evaluating gas dispersion in real time. Electrochemical sensors remain the most widely used sensors for CO and NO_x detection due to relatively low cost, portability, and sufficient accuracy for operational monitoring. These sensors are commonly integrated with portable gas detectors used by mine personnel during post-blast inspections. More advanced solutions include infrared and optical measurement systems which enable continuous monitoring of harmful gas concentration in ventilation air streams. Recent developments also include remote sensing methods and drone-assisted monitoring of post-blast gases, mainly in open-cast environments where rapid assessment of atmospheric dispersion is required. Comparison of post-blast gas detection and monitoring methods used in mining operations are shown in Table 3.

Table 3. Comparison of post-blast gas detection and monitoring methods used in mining

Detection method	Detected gases	Detection principle	Typical response time	Measurement range	Typical application
Electrochemical sensors	CO, NO, NO_2	electrochemical reaction producing electrical signal proportional to concentration	seconds (10-60 s)	ppm	underground mines, post-blast inspection
Infrared (NDIR) sensors	CO, CO_2	infrared absorption at characteristic wavelengths	seconds	ppm-%	fixed monitoring stations, ventilation air monitoring
Optical systems	NO, NO_2, NO_x	UV-visible absorption spectroscopy	seconds to minutes	low ppm	surface mining, research measurements
Portable multi-gas detectors	CO, NOx, O_2	combination of electrochemical and IR sensors	seconds	ppm	post-blast re-entry control
Remote sensing	NO_2, NO_x, CO	optical beam absorption across gas cloud	seconds to minutes	ppm over long distance	open-pit mines, environmental monitoring
Drone-mounted sensors	CO, NO_x	electrochemical or optical sensors integrated with UAV systems	seconds	ppm	open-pit blasting, research applications
Fixed ventilation monitoring systems	CO, NO_x	integrated sensor networks in ventilation airflow	continuous	ppm	underground mines

Ventilation plays a key role in reducing exposure to toxic and harmful gases in underground mines. Numerical models describing CO diffusion indicate that airflow velocity, ventilation system and re-entry time after blasting have a significant influence on gas dilution and clearance time [15]. As a result, the optimization of ventilation parameters is treated as an integral element of blasting design rather than a separate operational process.

3.3. Current state of emission

Recent studies have shown that the emission characteristics of explosives have changed as explosive formulations and blasting technologies have developed. Comparative analyses conducted by many researchers in recent years indicate significant differences in the volumes of toxic gases produced per kilogram of explosive, depending on explosive type and detonation conditions [7, 24]. Typical emission ranges reported in literature indicate that dry ANFO produces approximately 15-22 dm^3/kg of CO and 2-10 dm^3/kg of NO_x, while bulk emulsion explosives produce lower volumes, typically in the range of 8-15 dm^3/kg of CO and 1-3 dm^3/kg of NO_x. Dynamites are typically characterized by lower emission levels, reaching 4-10 dm^3/kg of CO and up to 5 dm^3/kg of NO_x, while permissible explosives intended for use in coal mining tend to show lower overall toxicity profiles. These results confirm that explosive composition and sensitization mechanisms have a significant influence on the completeness of detonation and the resulting emission profile.

The general trend observed in recent years indicates a gradual reduction in toxic gas emissions associated with the increased use of bulk emulsions and improved quality control of explosives. At the same time, research works emphasize that operational factors, such as moisture content, charge confinement and blast geometry remain equally important factors in determining the toxicity of post-blast gases. Therefore, modern approaches to emission reduction combine the chemical optimization of explosives with improved methods of blast design and monitoring practices, creating an integrated framework for safer and more environmentally responsible blasting operations.

Assessing global trends in toxic post-blast gases emissions remains challenging due to the limited availability of reliable and detailed data. Estimates of global or even European explosive consumption are often approximate, and information on the specific types of explosives used is rarely publicly accessible. Taking these limitations into account and taking advantage of the availability of detailed data on the Polish explosives market, this analysis focuses on how the total volume of toxic post-blast gases released into the environment in Poland has changed.

The Polish explosives market has undergone significant changes over the years, shaped both by broader economic transformations in the country and technological advances in the mining sector. In 1982, annual consumption reached approximately 42 thousand tonnes of explosives and 51 million detonators. As hard coal mining became mechanized in the following years, the demand for explosives decreased significantly, falling to approximately 33 thousand tonnes and 24 million detonators. The systemic and economic transformation of the 1990s led to further restructuring of the coal industry, resulting in a sharp reduction in consumption to 23.4 thousand tonnes of explosives and 11.7 million detonators.

The evaluation of changes in post-blast gas emissions over the analyzed period was carried out using data from 2000 and 2024. The analysis shows a clear improvement in the emission profile resulting from changes in blasting technology (Table 4). The volume of released gases during this period remained comparable, despite more than twofold increase in explosive consumption. A turning point was the introduction of bulk emulsions, which gradually replaced conventional products, such as ANFO and dynamites. Emulsion explosives were first used in Polish open-cast mining in the late 1990s, and since 2004 they have been introduced into underground mines. During the same period, Poland experienced sustained economic growth and intensive infrastructure development, which was reflected in a 106% increase in overall explosive consumption between 2000 and 2024.

Table 4. Approximate volume of post-blast gases generated in Polish mining in 2000 and 2024 [6, 18-23]

Explosive	Emission [dm^3/kg]		2000			2024		
	CO	NO_x	Consumption [Mg]	Emission [$dm^3/kg \times 10^6$]		Consumption [Mg]	Emission [$dm^3/kg \times 10^6$]	
				CO	NO_x		CO	NO_x
Bulk emulsion	10.35	0.55	1,100	11.39	0.61	37,080	383.78	20.39
Packaged emulsion	21.57	0.74	2,730	58.89	2.02	1,017	25.24	0.87
ANFO	18.80	7.12	5,350	100.64	38.11	6,170	116.00	43.93
Dynamite	4.02	2.98	8,220	33.06	24.51	3,850	15.48	11.47
TNT	309.7	0.16	360	111.49	0.06	0.010	3.10	0
Other*	–	–	5,480	164.70	13.33	0	–	–
Total			23,247	480.16	78.64	48,280	543.58	76.66

* – AN-based and AN-TNT explosives

The change in the volume of post-blast gas emissions between 2000 and 2024 is mainly related to the change in the assortment of explosives used in mining. In the past, dynamites, ANFO's, AN-based and AN-TNT based explosives were mainly used, while the current market is dominated by bulk emulsions. At the same time, the share of packaged emulsions has decreased, which is important from the point of view of environmental protection, since their chemical composition generally results in higher carbon monoxide emission compared to bulk emulsions. In recent years, the change in the type of explosive has stabilized. The overall consumption of explosives has also remained at a comparable level. When converting the estimated volumes of emitted post-blast gases into mass, the total emissions correspond to approximately 600 tonnes of CO and 15 tonnes of NO_x (expressed as NO_2). It should be highlighted that these values are still relatively small, since according to [25], approximately 2.14 million tonnes of CO and 0.49 million tonnes of NO_2 were emitted, indicating that emissions from blasting operations represent only a small fraction of overall atmospheric emissions in Poland.

4. Environmental impact assessment and legal framework

4.1. Toxicology of carbon monoxide and nitrogen oxides

As a result of the detonation of industrial explosives, gaseous reaction products are released, among which carbon monoxide and nitrogen oxides represent the most significant hazard to human health. The toxicological significance of these harmful gases has been widely documented in literature, providing the foundation for the gradual tightening of regulations governing blasting operations in mining and civil engineering.

Carbon monoxide is a colourless and odourless gas with a strong affinity for haemoglobin, approximately 200-300 times greater than of oxygen. As a result, exposure leads to the formation of carboxyhaemoglobin, which reduces the oxygen transport capacity of the bloodstream and causes tissue hypoxia. Early symptoms include headaches, dizziness and impaired coordination, while higher concentrations can lead to loss of consciousness and death. Nitrogen oxides exhibit different toxicological mechanisms. Nitric oxide (NO) is rapidly oxidized in air to nitrogen dioxide (NO_2), a highly reactive gas which irritates the respiratory tract and may cause delayed pulmonary edema upon exposure. The characteristic reddish-brown colour of NO_2 is commonly associated with visible post-blast fumes.

As a result, occupational exposure limits are defined with large safety margins. According to NIOSH guidelines, Immediately Dangerous to Life or Health (IDLH) values are set at approximately 1,200 ppm for CO, 100 ppm for NO and 20 ppm for NO_2. These values illustrate the significantly higher toxicity of nitrogen dioxide compared to carbon monoxide and justify the emphasis placed on NO_x reduction in modern blasting practice [20].

4.2. Environmental impact: acidification and tropospheric ozone formation

In addition to occupational safety issues, post-blast gases may contribute to local environmental impacts, especially in areas characterized by intensive blasting activity. Nitrogen oxides play an important role in atmospheric chemistry, acting as precursors to the formation of nitric acid and contributing to acidification processes of soil and water. In atmospheric conditions, NO_x participates in photochemical reactions leading to the formation of ground-level (tropospheric) ozone, which have a negative impact on vegetation, ecosystem stability and the health of human respiration [27].

Although emissions from blasting operations are typically episodic rather than continuous, large-scale open-cast mining operations can generate local NO_x plumes which can influence the air quality in surrounding areas. Oluwoye *et al.* [28] highlighted that blasting operations contribute globally to measurable NO_x emissions, highlighting their environmental importance and demonstrating that emissions associated with ammonium-nitrate-based explosives should be considered in broader assessments of atmospheric pollution. The environmental significance of such emissions depends on meteorological conditions, blast scale, and dispersion characteristics. Consequently, environmental regulations increasingly require operators to consider atmospheric conditions and potential gas dispersion as part of blast planning and risk assessment procedures.

4.3. Comparative analysis of legal regulations in Europe and Poland

The legal framework regulating explosives in the European Union is based primarily on Directive 2014/28/EU [29], which establishes essential safety requirements for civil explosives while harmonizing market access across member countries. Technical verification of explosive properties, including the assessment of toxic gas emissions, is carried out in accordance with the EN 13631 series of standards [30]. Part 16 of this standard (13631-16) specifies laboratory methods for sampling and measuring toxic gases, such as CO and NO_x. These standards harmonize testing methodologies but do not impose uniform quantitative emission limits, leaving it to individual member countries to define permissible thresholds within their national mining regulations.

Currently, legal regulations in Poland do not specify the maximum allowable concentrations of CO and NO_x emitted per 1 kg of explosive. Prior to the implementation of the EN 13631-16 standard, the applicable regulation was the now-withdrawn Polish Standard PN-C-86067:1997 [31]. This specified requirements for post-blast gases per 1 kg of explosive intended for underground use, set at 27 dm^3/kg for CO and 16 dm^3/kg NO_x. Furthermore, the requirements of the Regulation of the Minister of Family, Labour and Social Policy [32] on the maximum permissible concentrations and intensities of agents harmful to health in the working environment define the Threshold Limit Values in mg/m^3 depending on the exposure time during a work shift (Table 5).

Table 5. Maximum permissible concentrations of agents harmful to health in the workplace

Agent	Time-Weighted Average (TWA) [mg/m^3]	Short-Term Exposure Limit (STEL) [mg/m^3]
CO	23	117
NO_2	0.7	1.5
NO	2.5 (3.5*)	N/A (7.0*)

* – until 21 August 2026

In contrast, some European countries, such as Italy, Czech Republic and Slovakia, apply a combined toxicity limit (e.g. = 50-60 dm^3/kg), while Germany focuses primarily on the occupational exposure limits specified in the Technical Rules for Hazardous Substances (TRGS 900) [33]. Recent reductions in permissible exposure concentrations in Germany, particularly for NO_2 (0.7 mg/m^3), have significantly impacted blasting procedures and ventilation requirements, shifting the regulatory focus from product characteristics toward the workplace exposure control.

Recent studies have highlighted the lack of unified emission limits throughout the European Union and proposed the introduction of standard toxicity indicators based on emission volumes per kilogram of explosive. Such an approach would enable better comparability of explosives and facilitate harmonization of environmental and occupational safety requirements in the European mining sector. Overall, current regulatory trends indicate a gradual move towards more stringent occupational exposure limits, increased reliance on standardized testing methodologies and increasing emphasis on emission reduction at the source through improved explosive formulations and optimized blasting technologies.

5. Discussion

The findings presented in this review show that the explosives sector is currently undergoing a noticeable transformation. While efficiency and productivity have traditionally been the most important factors influencing blasting technology, environmental protection and occupational safety are now becoming equally important considerations. This shift reflects broader changes in the mining industry, where sustainability requirements and regulatory pressures are increasingly influencing technology choices and operational practices.

In the coming decade, one of the main challenges will be to maintain rock excavation efficiency while meeting stricter environmental expectations. Demand for raw materials, especially metals required for energy transition technologies and infrastructure development, is expected to remain high, maintaining the need for blasting operations worldwide. At the same time, regulatory trends in Europe indicate a continuous reduction in permissible exposure limits for nitrogen oxides and carbon monoxide, placing greater emphasis on emission control. Many research works and analyses reported by EFEE and ISEE, shows that modern solutions, such as bulk emulsion explosives, improved sensitization systems and electronic initiation can significantly reduce toxic gas emissions. However, these improvements do not completely eliminate emissions because the final gas composition remains strongly dependent on operational factors, including moisture conditions, confinement and blast design.

A significant problem identified both in research work and practice is the absence of consistent methodologies for assessing post-blast gases in real operating conditions. Although European standards, such as EN 13631 provide harmonized laboratory procedures, these tests are conducted in controlled environments which only partially reflect field conditions. In practice, emission levels are influenced by many factors, such as rock heterogeneity, weather conditions, ventilation efficiency and amount of explosives in large-scale blasts. As a result, emission data obtained from different studies are usually difficult to compare directly, even when similar explosive formulations are tested.

This lack of methodological consistency represents a significant obstacle to the development of uniform emission standards in Europe. Different countries use different approaches, ranging from limits for individual gases, through combined toxicity indices, to occupational exposure criteria. Without standard field measurement procedures, it remains difficult to compare explosive products objectively or to assess the actual environmental benefits of new technologies. The latest proposals highlight the need to link toxicity indicators to measurements obtained under operational conditions, which could contribute to both the harmonization of regulations and more transparent assessment of products on the European market.

Another important development direction is the growing role of digital technologies in blasting operations. Electronic detonators, automated monitoring systems and AI-supported blast design offer great opportunities to improve detonation efficiency and reduce the occurrence of incomplete reactions leading to higher emissions. However, the effectiveness of these solutions depends on the availability of reliable field data. Thus, the environmental benefits of digitalization, without consistent monitoring standards, remain difficult to quantify and verify.

From a technological point of view, further progress will likely focus on the development of low-emission explosive. Current research on catalytic additives, zeolite-based modifiers, hydrogen peroxide-based explosives, and TNT-free boosters suggests that chemical optimization can contribute to a reduction in toxic gases formation. At the same time, operational practices, such as moisture control, proper charge storage and optimal ventilation will continue to play a key role, since emission levels depend not only on explosive composition but also on the conditions under which detonation occurs. The results indicate that the evolution of explosive formulations and blasting technologies have had a tangible impact on the profile of post-blast gas emissions. Numerous studies shows that bulk emulsions generate lower amounts of CO and NO_x per kilogram than ANFO and dynamites, which is clearly reflected in the structural changes observed in the Polish explosives market. Even though the total consumption of explosives more than doubled between 2000 and 2024 – mainly due to economic growth and infrastructure expansion – the total volume of emitted gases remained similar, indicating substantial reduction in emissions per unit of explosive used. The key factor contributing to this improvement appears to be the gradual replacement of ANFO, dynamites, and packaged emulsions with bulk emulsions. When expressed in mass terms, blasting-related emissions remain relatively small compared to total national emissions. Nevertheless, it is important to remember that formulation of explosives do not only determine environmental impact. Field conditions, such as moisture, confinement and blast geometry still play a key role, highlighting the importance of combining material optimization with careful blast design and operational control.

Overall, the period between 2025 and 2035 is likely to be characterized by closer integration of technological innovation, environmental responsibility and regulatory developments. Establishing harmonized European approaches to in situ tests of post-blast gases seems to be a necessary step towards improving data comparability and supporting evidence-based regulation. Achieving this goal will require closer cooperation between research institutions, explosive manufacturers and mine operators. This would ensure that future standards reflect real operating conditions and contribute to reductions in the environmental impact of blasting.

6. Conclusions

- The presented analysis confirms that the explosives sector is undergoing a clear transformation from a results-oriented approach toward a model which increasingly takes into account environmental and occupational safety considerations. This transition is evident in both global and European market trends and notably in the structural changes observed in the Polish explosives market over the last two decades.
- Between 2000 and 2024, Poland saw a significant shift away from traditional explosives, such as ANFO, dynamites, and packaged products toward bulk emulsion explosives, which now dominate both open-pit and underground mining operations. Despite the substantial increase in the use of explosives, the overall amount of post-blast gases emitted over the considered period remained relatively stable. This proves a significant reduction in unit emissions per kilogram of explosive and confirms the environmental benefits associated with the latest emulsion-based technologies.
- Carbon monoxide and nitrogen oxides remain the most important toxic components of post-blast gases, both from an occupational and environmental point of view. Their formation is influenced not only by explosive formulation but also by operational parameters, such as moisture content, confinement conditions and blast geometry. Even though blasting-related emissions represent only a small proportion of total national atmospheric emissions, they are still of local significance and directly relevant to workplace safety. It should also be emphasized that, in certain cases, focus should not only be placed on these gases but also on ammonia, hydrogen sulfide, and sulfur dioxide.
- A key challenge identified in this study is the lack of harmonized European standards for evaluating gas emissions under real field conditions. Although laboratory methods are standardized, there is no unified framework for in situ measurements or consistent quantitative emission limits expressed per unit mass of explosive. Future progress in reducing the environmental footprint of blasting will therefore depend not only on technological innovation but also on the development of consistent monitoring standards and harmonization of regulations across Europe.

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