

Mining as a living system: insights from human biology for sustainable operations

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Abstract

Mining operations can be understood as living systems, with processes and impacts analogous to human body systems. Material flow mirrors the circulatory system, while ecosystems act as vital organs – lungs, kidneys, and skin – providing essential functions such as water purification and air quality regulation. Communities, akin to the nervous and immune systems, deliver critical feedback and resilience, enabling mining operations to adapt and thrive amidst challenges. This paper explores these biological analogies to explore a systems-thinking framework for mining operations, emphasising the balance between operational efficiency, environmental stewardship and social priorities.

Key strategies include adaptive management, biologically inspired innovations and integration of circular economy principles. By rethinking tailings as resources, leveraging real-time monitoring for proactive risk management and constructing climate-resilient infrastructure, the mining industry can address cascading effects and systemic interdependencies. This integrated approach enhances operational resilience, minimises risks and aligns mining practices with sustainability goals, laying the groundwork for the long-term success of both the industry and surrounding communities.

Keywords: *mining systems, responsible mining, sustainability, biologic systems, adaptive management, circular economy, tailings management*

1 Introduction: a systemic approach to mining and human biology

Mining operations, akin to human body functions, are intricate and highly interconnected systems. Each component, much like organs in a biological system, contributes to the overall functionality and health of the operation. Processes such as material transport, ore processing and waste management are the backbone of these systems. By recognising the parallels between biological systems and mining operations, a framework emerges for addressing operational inefficiencies and fostering sustainability.

The analogy between mining and the human body is not just a metaphor; it is a conceptual lens that encourages the viewing of operations as a cohesive whole rather than a series of isolated functions. This perspective provides several key benefits:

- Proactive management: identifying how disruptions in one process cascade into others enables companies to predict and address vulnerabilities before they escalate.
- Operational efficiency: examining systemic bottlenecks offers opportunities for streamlining resource use and improving throughput.
- Sustainability goals: aligning operations with principles of resilience and adaptability creates pathways to reduce environmental and social impacts while meeting, even surpassing, regulatory standards.

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- Health checks: by conducting ‘blood work’ tests on slurry samples, management and operators can quickly assess the geometallurgical behaviour or health of the process and modify conditions accordingly.

For instance, just as the body’s organs depend on a continuous supply of oxygenated blood, mining processes rely on the uninterrupted flow of materials. When logistics fail, the entire operation can grind to a halt, much as a blocked artery can endanger a human life. By viewing these interconnections through the biological analogy, companies can identify critical nodes and ensure their resilience.

Consider the mining industry’s response to climate-related disruptions. Deep mines implement advanced cooling and ventilation systems in response to rising underground temperatures, mirroring the body’s capacity to regulate its internal environment through sweating. This intervention not only safeguards workers but also reduces energy costs and greenhouse gas emissions. Similarly, adaptive strategies inspired by the immune system’s ability to fend off infections can inform how mining operations prepare for and respond to external threats, such as supply chain interruptions, cyber security threats or extreme weather events. These strategies might include real-time monitoring, predictive analytics and flexible contingency planning.

Expanding on this analogy offers mining companies a road map for sustainable innovation. For example, processes that are reliant on fossil fuels can transition to renewable energy sources, akin to how the body shifts to alternative energy pathways during fasting. Tailings are the finely ground byproducts remaining after ore processing, and viewing tailings and other byproducts as potential resources parallels the body’s efficient recycling mechanisms. Transparent communication and benefit-sharing initiatives build trust, much like the body’s thermal feedback loops maintain equilibrium.

By understanding mining operations as living systems, mining can develop integrated production strategies that not only address immediate challenges but also work with stakeholders to align with broader sustainability goals.

2 Core systems: analogies between mining and human biology

2.1 Circulatory system: material flow and logistics

The human circulatory system is a sophisticated network that ensures the efficient transport of oxygen, nutrients and waste, keeping the body healthy and functioning. In mining operations, this analogy extends to material flow systems, where pumps and pipelines, conveyors, haul trucks and distribution networks serve as the arteries and capillaries of resource movement. Efficient logistics ensure that ore, water, slurries and waste are transported effectively from extraction to processing, while bypass strategies address system inefficiencies, preventing costly disruptions and environmental risks.

Arteries in the circulatory system represent the large-scale movement of materials over long distances. In mining, bulk ore is transported from extraction sites to processing plants through conveyors, haul trucks or slurry pipelines, sometimes through kilometre-long conveyor belt systems to transport ore directly from the mine to the processing facility or a port, reducing reliance on haul trucks and minimising energy consumption and emissions.

Capillaries, in contrast, represent finer material distribution within processing plants, ensuring that ore and slurries reach specific units such as crushers, grinding mills and flotation cells. This level of precision ensures optimal recovery rates and process efficiency. Many mines are implementing smart distribution systems using sensors and real-time data to control ore flow to different circuits, reducing energy use while improving metal recovery.

When blockages occur in the human circulatory system, medical interventions like coronary bypasses restore critical blood flow. Circulatory restoration strategies offer innovative ways to improve efficiency, manage risk and minimise environmental impact. In mining, similar strategies can be employed to reroute materials, manage waste and prevent operational blockages. Examples of the implementation of bypass strategies include:

1. Some mines have developed tailings bypass systems to transport tailings to a new, more secure storage site or to reduce water contamination risks. Some systems have included pipelines and pumps designed for varying tailings densities. This rerouting reduces pressure on the primary tailings facility and improves overall site stability, much like redirecting blood flow around a weakened artery to prevent failure or stopping blood from flowing through a damaged area, ensuring systemic health.
2. A mining company in Indonesia (Huayou Cobalt 2024) installed emergency bypass systems for slurry pipelines in an area prone to landslides and earthquakes. When a landslide damaged a section of the main pipeline, the bypass system quickly redirected slurry flow, minimising downtime and avoiding significant financial losses. These emergency measures ensured operational continuity, mirroring how a circulatory bypass prevents life-threatening complications.

Despite the importance of efficient transport, mining logistics also have challenges such as high energy demands, maintenance requirements and variability in ore properties. Just as the circulatory system relies on healthy vessels, mining infrastructure requires robust design and proactive management to prevent failure. For example, traditional large-scale conveyors and haul trucks consume significant energy. To address this, some mines have implemented regenerative conveyor systems that generate electricity during downhill ore transport, reducing energy use across the operation. Similarly to how arteries experience wearing under stress, mining conveyors and haul trucks require predictive maintenance strategies. Some mines have transitioned to a conveyor system with advanced wear sensors, reducing maintenance costs and operational downtime. Fluctuations in ore properties, such as particle size or moisture content, can disrupt transport efficiency. Some mines have implemented a real-time monitoring system that automatically adjusts conveyor speeds and cleaning mechanisms based on ore characteristics, preventing bottlenecks.

Efficient material flow, combined with adaptive bypass strategies, mirrors the circulatory system's role in maintaining health and balance. Just as a healthy vascular system ensures the body thrives, mining companies must maintain robust logistics networks to ensure operational stability, safety and sustainability. By investing in predictive maintenance, adaptive bypass systems and energy-efficient technologies, mining companies can enhance both operational efficiency and environmental performance, ensuring the long-term resilience of their operations.

2.2 Respiratory system: ventilation and air quality

The respiratory system provides oxygen, particulate filtration and thermal regulation, and expels carbon dioxide. In mining, ventilation systems serve as the lungs and are particularly critical for underground operations and air quality management. Just as the lungs filter out harmful particles and regulate oxygen intake, ventilation systems in mining remove dust and gases while ensuring a continuous supply of fresh air for underground operations. Effective ventilation systems not only ensure worker safety but also align with environmental compliance standards.

Ventilation optimisation is essential in both ensuring the safety of workers and maintaining energy-efficient operations. Mining ventilation systems, akin to the lungs, facilitate air exchange, removing harmful gases and particulate matter while delivering fresh oxygen to underground environments. Advances in dynamic ventilation control allow mines to adapt airflow to operational needs, much like the body adjusts breathing rates based on altitude and activity levels.

Energy-efficient technologies, such as variable-speed fans, reduce power consumption while maintaining consistent air quality. Monitoring systems that detect concentrations of toxic gases like methane or carbon

monoxide further enhance safety and compliance. Integrating renewable energy sources for powering ventilation systems can significantly reduce the carbon footprint of underground operations. Examples include:

1. Australian gold mines (e.g. Agnew Gold Mine) (MINETEK 2024) have pioneered energy-efficient ventilation systems that use real-time sensors and artificial intelligence (AI) to adjust airflow dynamically. These systems have achieved the dual benefit of lowering greenhouse gas emissions and ensuring worker safety by maintaining optimal air quality. This innovation mirrors the adaptability of the respiratory system, which adjusts oxygen intake during physical exertion to meet increased demand.
2. Several mines in Canada have implemented comprehensive ventilation monitoring systems that reduce energy use. These systems employ advanced sensors to detect air quality metrics and adjust ventilation rates accordingly, preventing unnecessary energy expenditure while safeguarding workers. This approach exemplifies the importance of tailoring air circulation to real-time conditions, much like how the body regulates breathing during rest versus exercise.

Dust management in tailings facilities during operation and closure can be effectively compared to the human body's respiratory system and skin, both of which protect against harmful airborne particles and pathogens. When dust from tailings facilities becomes entrained in the air it can pose significant health and environmental risks, much like how airborne pathogens can harm the lungs if inhaled. Much like how the body adapts over time to environmental stresses, long-term strategies for managing dust and tailings need to account for climate variability and long-term stability, such as implementing progressive closure techniques using incremental capping and revegetation during operations rather than waiting until mine closure.

Drawing inspiration from biological systems, several mitigation strategies parallel the body's natural protective mechanisms. The human respiratory system relies on mucous membranes to trap particles and prevent them from entering the lungs. Similarly, surface moisture retention, effected by 'continuous' surface watering or polymer-based dust suppressants, can prevent dust from becoming airborne in tailings facilities. The cilia in the respiratory system sweep particles away from sensitive lung tissues, much like vegetative barriers can act as physical filters in mining operations. Native grass seeding and bioengineered vegetative mats have been used to resist erosion, anchor loose materials and trap dust.

Just as alveoli in the lungs capture fine particles before they enter the bloodstream, dust filtration systems and air curtains can intercept airborne dust before it spreads. Mines often use dust extraction systems placed along haul roads or near tailings storage facilities (TSFs) to capture and filter dust-laden air. Artificial structures like wind fences can be installed along the perimeters of tailings facilities, reducing wind speed and emissivity.

The body's immune system deploys targeted responses to pathogens and, similarly, biological solutions can be used to stabilise dust in mining. Some microbes produce biofilms that bind particles together. Certain strains of cyanobacteria and fungi can be applied to tailings surfaces to form biological crusts. The use of fungal networks to trap and bind fine particles is like how macrophages trap foreign particles in the body.

By considering the parallels between the human respiratory system and dust management strategies in mining, a more holistic and biologically inspired approach can be developed. Moisture control, physical barriers, biological stabilisation and adaptive long-term planning can collectively reduce dust risks while promoting environmental resilience. As in the human body, redundancy and multi-layered protection ensure greater overall system health, emphasising the importance of proactive dust mitigation in modern mining operations.

2.3 Digestive system: ore processing and waste management

The human digestive system efficiently extracts nutrients from food while managing waste, processes mirrored in mining operations where ore undergoes various stages to extract valuable minerals while

minimising waste generation. The effectiveness of ore processing directly influences resource recovery, operational efficiency and environmental sustainability.

In ore processing, raw material passes through multiple stages designed to break down and refine the ore for maximum mineral extraction. The process begins with in-pit operations, where selective mining techniques target high-value ore zones while leaving lower-grade material untouched. This strategy, akin to dietary adjustment for nutrient optimisation, reduces unnecessary processing of waste material and improves efficiency from the outset.

Following selective mining, the ore undergoes crushing and grinding to break it into smaller particles, increasing the surface area for mineral liberation. Techniques such as high-pressure grinding rolls (HPGRs) and semi-autogenous grinding (SAG) mills play a critical role at this stage. In the body, digestive enzymes break down complex food into simpler molecules that the body can absorb efficiently, minimising waste. Similarly, HPGR technology breaks down ore more efficiently with less energy consumption, reducing operational strain and optimising mineral recovery; much like how the body minimises energy use in nutrient absorption.

Further refinement occurs through selective sorting and multiple circuits which use advanced sensor-based, ore-sorting technologies to separate waste rock before it enters the process plant. This process mirrors the body's ability to selectively absorb essential nutrients while discarding non-essentials. Technologies such as X-ray transmission (XRT) sensors detect ore density variations, ensuring that only valuable material advances for further processing.

Inside the process plant a range of extraction methods is employed, including flotation, where air bubbles selectively attach to valuable minerals, allowing them to float while non-valuable materials sink. New innovations in flotation technology, such as the use of nanobubbles, are improving fine particle recovery by increasing the surface area for attachment, while coarse particle flotation techniques have been developed to reduce energy consumption and improve the handling of tailings. The use of nanobubbles and coarse particle flotation enhances mineral recovery by increasing the surface area for valuable minerals to interact with air bubbles. This innovation can be compared to the body's microvilli in the intestines, which increase the surface area for nutrient absorption. Just as the microvilli optimise the efficiency of nutrient uptake, nanobubbles improve the extraction of fine particles, while coarse particle flotation reduces energy demands by targeting larger fragments earlier in the process.

Similarly, leaching processes use chemical solutions to dissolve target metals for extraction. Cyanide leaching in gold recovery and solvent extraction-electrowinning for copper are widely used, reflecting the body's enzymatic breakdown of nutrients for absorption.

Real-world mining operations exemplify these techniques:

- At many locations, significant operational inefficiencies are related to the presence of high concentrations of smectite clay in the ore. Clay minerals can lead to increased viscosity in processing circuits, affecting the efficiency of flotation and leaching processes. They may also cause equipment blockages and reduce the permeability of heap leach pads, leading to decreased metal recovery rates. To address these challenges, mining operations often implement strategies such as ore blending, the use of dispersants and modifications to processing techniques to manage the impact of clays on metallurgical performance.
- At the La Coipa mine in Chile, the grinding circuit was modified to increase throughput by pre-screening the SAG mill feed, which maximised power utilisation of the pebble crusher in the semi-autogenous ball mill crusher circuit (Julio & Jorge 1994). This modification resulted in a 10% increase in mill throughput with relatively low investment costs. The Las Bambas copper project in Peru incorporated IsaMills™ in the regrind circuit to achieve a precise size distribution with minimal over-grinding, enhancing overall processing efficiency (Ausenco 2021). Chewing food and enzymatic breakdown in the stomach pre-condition it for efficient nutrient extraction later in the

intestines. Similarly, pre-screening the ore before SAG milling reduces the load on the crushing circuit, improving overall throughput and energy efficiency.

- Many mines are employing sensor-based ore sorting using XRT technology. TOMRA reports that at the Mt Carbine tungsten mine in Australia, implementation of this technology has allowed the operation to process only 10% of the mass in the wet plant, dramatically cutting running costs, reducing the required size of the wet plant, and saving water and energy (TOMRA 2024a). At Vista Gold's Mt Todd project in Australia, using two-stage sorting led to a 10% improvement in feed grade to the mill and reduced operating costs by eliminating the need to process waste material (TOMRA 2024b). Ore sorting can be likened to the body's ability to selectively absorb essential nutrients while discarding waste. The body's cell membranes and selective permeability allow only necessary molecules like glucose, amino acids and vitamins to pass into the bloodstream while rejecting waste. Similarly, XRT technology allows valuable ore to be identified and separated from waste rock early in the process, reducing energy consumption and waste generation.
- Several mines are implementing advanced flotation technologies including nanobubble generation and coarse particle flotation, enhancing concentrate recovery and reducing tailings volumes. The presence of nanobubbles increases the flotation rate constants across various particle size ranges, leading to enhanced separation efficiency.

As the industry evolves, innovative technologies continue to shape ore processing practices. In situ recovery offers a transformative approach, where minerals are dissolved directly within the orebody and pumped to the surface, reducing surface disturbance and eliminating the need for extensive waste management. AI-driven process control systems are also gaining traction, enabling real-time monitoring and adjustments to grinding and flotation parameters for improved recovery efficiency. Other promising developments include bioleaching, which uses bacteria to break down sulphide ores in copper and nickel operations, and microwave-assisted comminution, which reduces energy use in grinding by pre-fracturing ore particles.

These continuous advancements in ore processing aim not only to optimise resource recovery but also to reduce environmental impacts, promote operational efficiency and align with circular economic principles for long-term sustainability.

2.4 The brain and the nervous system: coordination and control

The human brain is the command centre of the body: not merely a recipient of blood flow but the core of decision-making, coordination and system regulation. It processes vast amounts of sensory data, directs responses, balances long-term strategies with short-term reactions and prioritises the wellbeing of the entire organism. This same concept applies to the mining industry, where centralised decision-making systems must oversee the interconnected operations, risks and sustainability efforts of an entire site.

In mining, the role of the 'brain' can be analogised to an integrated governance and control system responsible for balancing operational efficiency, environmental protection and social accountability. Like the brain balancing immediate survival with long-term health, modern mining governance must move beyond short-term financial returns. Just as the brain prioritises the protection of the body from harm, the mining brain must prioritise human safety, infrastructure stability, and environmental protection.

Rather than focusing solely on optimising isolated processes, the mining brain must understand the complex interplay between systems of systems. This involves AI-powered control systems, strategic leadership teams and real-time monitoring platforms that synthesise data across departments to guide holistic decision-making.

Corrigan & Ikonnikova (2024) highlight additional opportunities and challenges in AI use for mining, particularly in multi-objective optimisation. While AI can optimise performance and risk reduction, it must also be applied in ways that align with broader sustainability and social justice goals. Ethical AI use involves bias mitigation (algorithms used in decision-making must be trained on diverse datasets to avoid reinforcing historical biases, particularly in environmental justice contexts), transparency (AI models should be

interpretable and transparent to stakeholders, ensuring decisions can be traced and justified) and inclusive decision-making (integration of AI in mine governance should include input from community stakeholders, environmental groups and independent experts). AI can serve as the operational brain that harmonises productivity with safety and environmental responsibility.

The nervous system integrates sensory data and coordinates responses. The human nervous system offers a powerful metaphor for the interconnected, responsive nature of modern mining operations. From real-time data sensing and automated responses to crisis management and community engagement, the principles of coordination, feedback and adaptability are critical for the health and sustainability of a mining system. Mining uses advanced control systems like supervisory control and data acquisition (SCADA) to manage operations. Automation and AI are increasingly integral to achieving operational excellence.

The nervous system not only responds to immediate threats but also detects subtle signs of fatigue or imbalance, triggering preventive actions. Similarly, predictive maintenance systems in mining use AI and sensor data to anticipate equipment failures before they occur. During times of injury or crisis, the nervous system heightens alertness and prioritises life-saving functions. Similarly, mining control systems must adapt rapidly to emergency situations, prioritising critical responses. As technologies such as advanced sensors, AI, digital twins and predictive maintenance evolve, mining systems are becoming increasingly capable of managing complexity with the same sophistication as the human body. The mining industry is increasingly leveraging AI and digital technologies to enhance safety and material flow management. Emerging trends in ventilation technology include the integration of AI and the internet of things (IoT) to predict air quality issues before they arise. For example, predictive algorithms can identify areas at risk of gas build-up and increase airflow pre-emptively, much like how the body increases breathing rates in response to low oxygen levels. AI-driven distribution systems can continuously adjust ore flow based on real-time feedback, ensuring a balance between process stability and energy efficiency. This holistic, system-of-systems approach emphasises the importance of balancing operational efficiency with environmental protection and social responsibility. These systems mirror the body's nervous system by processing signals and coordinating swift responses to potential disruptions.

Integrated control systems enable centralised monitoring and control of complex operations. By consolidating real-time data, SCADA enhances operational efficiency, akin to how the brain processes sensory inputs to coordinate bodily functions. Additionally, environmental, social and governance (ESG) frameworks function as reflexes, prompting immediate actions to address social and environmental demands while maintaining operational stability.

The future of mining coordination lies in fully autonomous operations. AI-driven platforms that integrate data from drones, IoT devices and real-time sensors can optimise decision-making with minimal human intervention. Developing cognitive digital twins, modelled after brain activity, provides mines with the ability to simulate complex scenarios and predict system-wide outcomes before implementation, similarly to how the brain visualises outcomes during decision-making. This evolution mirrors advancements in neurology, where researchers explore artificial neural networks to replicate complex decision-making processes. Autonomous systems in mining promise safer, more efficient and environmentally friendly operations.

2.5 The skin and the skeletal system: structural integrity

The skeletal system provides structural support and protection for the human body while facilitating movement and stability. In mining operations, the skeletal system can be compared to the physical infrastructure that ensures the stability and integrity of a mining site. Key elements include mine shafts, tunnels, tailings storage embankments, retaining walls and pit slopes – all of which must be carefully engineered to provide support, prevent collapse, and protect workers and the environment.

Just as the bones of the human body bear loads and prevent collapse, mining operations require robust structural frameworks to maintain safety and operational efficiency. Underground mining tunnels, for instance, must be reinforced with rock bolts and shotcrete, like how bones must be strong enough to support

the body's weight and resist fractures. Failures in this structural system, much like bone fractures, can have catastrophic consequences, including mine collapses and worker fatalities.

The skeletal analogy extends to pit slope stability in open-pit mining, where benches and slopes must be carefully engineered to prevent landslides. Advanced monitoring tools, such as LiDAR and ground-penetrating radar, act like the body's proprioceptors, continuously scanning for stress or instability in the rock mass.

The embankments of TSFs are analogous to the rigid structures of the skeletal system. These engineered barriers must resist stress, erosion and seismic activity while containing the tailings. Just as bones can deteriorate from osteoporosis, tailings dams can weaken due to poor construction or water saturation, increasing the risk of failure.

The skin, the body's largest organ, serves as a protective barrier against pathogens, regulates temperature and facilitates healing after injury. Similarly, the surface of a mining site – soil, vegetation and surface drainage systems – functions as the protective barrier between mining activities and the environment. When compromised, both the human skin and the surface environment become vulnerable to external threats.

The skin prevents infections and fluid loss, much like topsoil and vegetation protect landforms from erosion. When vegetation is cleared for mining activities, the exposed soil becomes vulnerable to erosion, leading to sedimentation in nearby water bodies and ecosystem degradation. After mining operations cease, restoring the site to a stable and productive state is essential, akin to how skin heals after an injury. Effective mine closure strategies focus on restoring surface stability, controlling erosion and ensuring vegetation regrowth. The skin also regulates fluid balance and prevents excess water loss. Geotextile covers can be considered to act like synthetic skin, preventing wind erosion and limiting dust emissions. Evapotranspiration barriers and natural crust formation through mineral precipitation, like how scabs protect healing skin, can limit dust release during dry periods. Similarly, surface water management in mining requires proper drainage channels, water retention ponds and flood protection systems to prevent contamination and erosion during extreme weather events.

In a fully integrated mining system, the 'skeletal and skin' systems must work together, just as they do in the human body. Structural integrity (the skeletal system) ensures the safe functioning of the operation, while surface protection (the skin) minimises environmental harm and supports long-term stability. Advanced monitoring systems, such as ground-penetrating radar for slope stability and remote sensing for surface erosion, act like the body's sensory neurons, providing early warnings of potential risks.

The skin is an area of active work in mining. For example, inspired by the skin's regenerative capacity, bioengineered covers using microbial growth and vegetation are being tested for tailings management to stabilise slopes and improve water retention. Similarly to bone grafting for weakened bones, geosynthetic liners and reinforcements are increasingly used in TSF embankments to provide additional structural support and prevent seepage. Smart monitoring systems that use fibre-optics and IoT sensors are becoming more common in mining infrastructure, providing real-time feedback on stress, deformation and water movement.

These biological analogies not only help explain the importance of structural integrity and surface protection but also emphasise the need for continuous monitoring, proactive risk management and investment in closure planning to ensure the long-term health of mining operations and their surrounding environments.

3 Expanding the analogy: interdependencies and cascading effects

The human body under stress provides a powerful analogy for understanding how complex, interdependent systems behave during crisis, much like mining operations experiencing operational or environmental stress. In both cases, stressors can trigger cascading effects across multiple systems, sometimes leading to systemic failure if not addressed promptly. Both human biology and mining systems exhibit cascading effects when one component fails. For example, a blocked artery strains the heart, brain and other organs. In mining operations, disruptions in energy supply can cause ventilation failure which halts operations, affecting logistics, worker safety and ore processing. In seismically active areas, early detection of stress allows for

proactive water diversion, preventing both physical failure and downstream contamination. Failure in tailings management due to inadequate water diversion during extreme weather can impact downstream processing plants and halt production. Diagnosing, responding to and managing such situations is often complex, requiring continuous feedback, proactive adaptation and cross-system coordination.

When the body experiences a significant stressor, such as an infection, injury or chronic disease, multiple systems react in a series of interconnected ways. For example, a viral infection can trigger an immune response where white blood cells target the pathogen. However, an overreaction, like a cytokine storm, can lead to systemic inflammation, causing damage to healthy tissues and multiple organ failure. Stress on the heart, such as from high blood pressure or a blocked artery, can limit oxygen delivery to critical organs. This may trigger a heart attack, which can further impact kidney function, cognitive health and muscle performance as oxygen and nutrient delivery falters. If the kidneys or liver fail to detoxify the bloodstream properly, toxins accumulate. This can cause neurological symptoms (like confusion or seizures) and cardiovascular complications as waste products build up, further straining the body's ability to function. Severe physical stress can trigger the brain to shift into a survival state, prioritising critical functions while limiting fine motor skills, memory and decision-making capacity – potentially compounding the stress response and impairing recovery efforts. In all cases, feedback between systems means that stress in one area can quickly propagate through the entire body. Identifying the root cause often requires complex diagnostics, while treatment must address both the immediate symptoms and underlying causes simultaneously. This complexity parallels challenges in managing mining operations during crises.

In mining operations, stressors can manifest as ore variability, equipment failure, natural disasters, regulatory challenges or safety incidents. Like the body, the mining operation consists of interdependent systems – each playing a critical role in maintaining operational health and safety. Stress in one area can trigger failures elsewhere, often with increasing complexity. Heavy rainfall (external stress) may overwhelm TSF drainage capacity, increasing pore water pressure and threatening dam stability. Real-time monitoring may detect rising water levels, and engineers implement water bypass measures to divert excess run-off, much like how the body dilates blood vessels to reduce pressure. If the stress continues, the structural integrity of the dam could degrade, similarly to how prolonged high blood pressure damages artery walls. A dam breach would release tailings, contaminating local water sources, impacting nearby communities and triggering regulatory penalties. This mirrors how organ failure can trigger widespread complications across the body. Early intervention strategies like reinforced embankments and proactive water management resemble preventative health care, such as medications for blood pressure control.

Another example lies in ore variability, which may be unanticipated and cannot be controlled, and which may cause process imbalance. A sudden change in ore quality with a higher clay content can disrupt the flotation circuit, reducing recovery rates. Process control systems can be used to adjust reagents and airflow, like how the nervous system regulates enzyme production when digestion issues arise. If the adjustment is insufficient, tailings volumes may increase and recovery rates may decline, leading to higher operational costs and increased waste. Poor flotation efficiency may affect water balance in the thickening circuit, requiring additional treatment capacity. If unmanaged, this could also impact TSF stability. Advanced monitoring systems and machine learning for ore sorting resemble the body's ability to adapt digestion processes to dietary changes.

Consider cascading effects initiated by failure in a grinding circuit. Failure of a primary ball mill gearbox would halt grinding operations. Backup circuits could reroute ore to a secondary mill, akin to the body's ability to redistribute blood flow during trauma. If the secondary mill is unable to handle the full load, ore stockpiles build, delaying downstream processes and reducing production rates. Prolonged downtime strains financial resources and may lead to reputational damage with investors, much like how unaddressed cardiovascular stress can lead to multiple organ strain. Predictive maintenance technologies, such as vibration monitoring sensors, mimic how the nervous system detects physical discomfort before injury occurs.

The body's response to stress provides several key insights for mining operations. Just as pain receptors alert the brain to stress, mining operations benefit from real-time sensors, predictive models and AI-driven

analytics for early stress detection. No mining system operates in isolation. An issue in tailings management can affect water treatment, while a breakdown in ore processing can strain waste-handling capacity. Diagnosing the full scope of system interactions requires a whole-system perspective. Preventative health care focuses on long-term wellbeing rather than short-term symptom relief. Mining operations should similarly invest in predictive maintenance, climate-resilient infrastructure and community engagement rather than waiting for failures to occur. Just as the body has backup systems (e.g. collateral blood vessels, immune system redundancy), mining operations need redundant circuits, flexible ore handling routes and emergency response plans to manage unexpected stress events. Post-stress recovery requires both repair and adaptation, whether it involves a patient recovering from surgery or a mine stabilising a damaged TSF through long-term reclamation efforts.

Cross-departmental coordination is a crucial strategy to mitigate such risks. Integrated risk management frameworks, which include real-time data sharing between departments, enable faster responses and adaptive decision-making. Advanced digital ecosystems that integrate IoT devices and AI-driven analytics hold promise for mitigating cascading effects. These technologies create dynamic systems where predictive algorithms identify vulnerabilities and suggest coordinated responses. For instance, smart sensors placed in critical infrastructure can provide early warnings of stress or failure, while AI systems dynamically allocate resources to stabilise operations. These innovations mirror the body's ability to adapt to injury or illness by reallocating energy and resources to maintain critical functions.

The human body's response to stress provides a compelling model for understanding the cascading effects within mining systems. Just as organ failure or infection can ripple across the body, stressors in mining operations can trigger systemic disruptions if left unmanaged. By integrating whole-system monitoring, proactive adaptation and resilience strategies inspired by the body's natural defences, mining operations can better manage risks, improve operational stability, and reduce long-term environmental and social impacts.

Much like in medicine, diagnosing and treating mining stress events requires a comprehensive understanding of how interconnected systems function together. Recognising these dynamics can lead to more holistic, resilient and sustainable mining practices – ensuring the health of both the operation and the surrounding environment. As suggested by Nelson (2023), the mining industry should consider tailings as the bloodstream of a mining operation. In the historical days of medicine, blood was recognised as vital, but it was not well understood until the 17th century. Today a visit to the doctor's office often starts with an order of blood tests – the backbone diagnostic tool used to search for markers of diseases and health conditions. The mining industry would learn a lot by adopting such an approach to understanding its geometallurgical flow and tailings, and to potentially diagnose issues analogous with disease and poor health in mining and extractive processes. We need 'blood work' to understand the effectiveness of new methods of mining, comminution, separation and extraction, and to understand the condition of tailing slurries that impacts transport, thickening and filtration. If we do the blood work we will be able to evaluate real opportunities for increased extraction efficiency and the waste stream segregation or partitioning needed to apply a zero-waste and re-use philosophy. Blood work will also provide the basis for understanding the occurrence, distribution and sequestration of critical minerals and metals in the tailings as we consider remining or secondary (byproduct) production for the energy transition.

4 Adaptation and resilience: lessons from the immune system

The human body's ability to respond to stress, injury and pathogens serves as a powerful model for adaptive resilience. The human body has highly developed systems to adapt, heal and maintain homeostasis. For instance, when faced with a detected infection, the immune system kicks into action and, when injured, tissues begin to repair themselves. Predictive climate models allow mining operators to anticipate extreme weather events, enabling proactive measures to protect critical infrastructure. Diversifying energy sources, such as incorporating renewable energy, reduces dependency on vulnerable supply chains and enhances operational stability. Climate-resilient infrastructure, such as reinforced tailings dams and flood-resistant roadways, mitigates the physical risks associated with severe weather.

Just as the immune system builds resistance through past exposure, mining operations can develop resilience by learning from historical challenges and integrating those lessons into ongoing processes. Using predictive models that account for geometallurgical variability can improve tailings management by preparing for, and mitigating, risks before they become serious, akin to preventative medicine. Adaptive strategies in mining involve real-time monitoring, predictive modelling, and flexible process adjustments to maintain stability and efficiency. By investing in systems that can anticipate and quickly respond to stressors, mining companies can improve resilience, minimise downtime and reduce the risk of catastrophic failures. This approach emphasises the importance of being proactive rather than reactive, much like how the human body's immune system works to prevent illness before it becomes severe. Key components of adaptive mining operations include:

- Predictive monitoring and data-driven adaptation – real-time sensors and predictive analytics allow mining operations to detect ore variability, structural stress and environmental stressors early. This data, much like the immune system's feedback mechanisms, enables proactive adjustments, such as modifying flotation parameters or adjusting water levels in tailings dams before stress events escalate. An example is found at a platinum mining company in South Africa that experienced significant fluctuations in ore quality, which negatively impacted the efficiency of its flotation circuit and led to inconsistent metal recovery rates (Barkhuysen 2010). Instead of sticking to a fixed process set-up, the company implemented an adaptive response strategy. They installed real-time ore characterisation equipment, such as automated mineral analysers, to measure mineral composition and ore hardness as the ore entered the mill. Using machine learning algorithms, the data from the analysers was used to dynamically adjust the flotation parameters, such as reagent dosing and aeration rates. This adaptation allowed the company to optimise metal recovery based on the specific properties of each batch of ore, maintaining high efficiency despite variability.
- Climate resilience and infrastructure adaptation – the immune system adjusts its responses based on the severity of threats. Similarly, mining operations can prepare for climate stress by reinforcing tailings dams, diversifying energy sources and installing flood-resistant infrastructure to withstand extreme weather events, such as reinforced embankments and water management systems for flood mitigation. Some mining operations in Alaska and Canada are having to contend with increasingly unpredictable weather patterns due to climate change, including heavier rainfall and rapid snowmelt. These events may cause flooding and increased the risk of tailings dam overflow. To adapt, companies often develop a climate resilience plan that includes real-time weather monitoring and automated drainage systems. The weather monitoring system may use satellite data and local weather stations to provide early warnings of heavy rainfall and an automated drainage system could be activated to divert excess water away from critical areas and prevent flooding.
- Operational flexibility and continuous learning – the body's adaptability involves cross-system cooperation and constant recalibration. Mining companies can foster operational flexibility through cross-trained staff, modular process designs, and adaptive maintenance strategies capable of adjusting to both expected variations and sudden disruptions. For example, maintenance scheduling can be used to preclude frequent equipment failures, perhaps due to the abrasive nature of ore. Vibration sensors, temperature monitors and machine learning algorithms may be used to assess the health of critical equipment continuously and dispatch crews to address the issue before a breakdown occurs. This approach can minimise unplanned downtime, extend the life of expensive machinery and provide the information to optimise the inventory of spare parts, reducing costs and improving overall efficiency.

Mining companies are also acting to expand their adaptive capacity in several ways, including the development of cross-training employee programs that can provide reliable flexibility to ensure that operations can continue smoothly if unexpected challenges arise, much like how the body uses different energy sources depending on the situation.

Mining companies are building virtual models of mining infrastructure to simulate extreme weather scenarios, stress-test system vulnerabilities and optimise emergency response plans. Advances in digital twinning technology offer promising applications for resilience in mining. By creating virtual models of infrastructure and processes, operators can simulate extreme weather scenarios, identify vulnerabilities and optimise responses. Additionally, integrating AI-driven decision-support systems with IoT devices enables real-time adjustments to changing conditions, such as altering water flow in tailings dams or redistributing power during outages. These technologies emulate the immune system's ability to detect and neutralise threats dynamically.

Mining companies can also use adaptive strategies to enhance social resilience by collaborating with local communities, regulators and environmental organisations. Transparent communication, shared risk management planning and investments in community development contribute to long-term operational stability and community trust.

Like how the body relies on multiple systems for healing and stress management, mining operations can integrate environmental restoration efforts such as wetland rehabilitation, vegetation buffers around TSFs and biodiversity offsets. These strategies not only enhance ecological stability but also help companies meet regulatory requirements and reduce long-term liabilities.

By developing proactive adaptive resilience strategies inspired by the immune system, mining operations can respond more effectively to both operational and environmental challenges while safeguarding human health and ecological stability. Just as the immune system defends the body from threats before they escalate, proactive approaches in mining can mitigate risks, enhance performance and contribute to long-term sustainability. Embracing flexible, data-driven strategies that anticipate and respond to stress will enable mining companies to not only survive but thrive in a rapidly changing global landscape. Staying ahead of stressors requires continuous innovation. Mining companies should invest in research and development to explore new technologies and strategies for adaptive management. This investment is analogous to how the body's immune system evolves to recognise and combat new pathogens over time.

5 Sustainability: systemic health in mining

Sustainability in mining, like health in the human body, depends on systemic balance and efficiency. Sustainable tailings management, for example, focuses on reducing long-term waste impacts, akin to how the body neutralises and removes toxins. Viewing sustainability as systemic health emphasises that the overall wellbeing of a mining operation mirrors the health of a living organism.

When the human body functions optimally, networks like the circulatory, immune and skeletal systems work together seamlessly. Similarly, a sustainable mining operation must ensure efficient resource extraction, waste management, environmental stewardship and community engagement. If one aspect becomes unsustainable it can destabilise the entire operation, just as an illness can disrupt the body's balance.

This analogy encourages mining companies to adopt a holistic perspective, moving beyond short-term profit to consider broader environmental, sustainability and social impacts. By doing so, they can make decisions that promote long-term resilience and sustainability.

The principles of a circular economy offer a pathway for achieving systemic health by prioritising waste valorisation and resource efficiency. For instance, encapsulating hazardous materials in tailings mirrors the body's ability to neutralise toxins. Water and energy recycling further enhances resource efficiency, aligning mining practices with sustainability goals. Social impact assessments and ESG metrics provide accountability, ensuring that projects benefit both communities and the environment. For example:

- A major iron ore producer in Australia (Fortescue 2024) integrated carbon management across its operations. By investing in renewable energy projects, such as solar and wind power, and implementing energy efficiency measures in transport and milling, the company reduced greenhouse gas emissions and enhanced its environmental footprint. Reforestation projects complemented these efforts, improving local biodiversity and sequestering carbon. This systemic

approach treated carbon management as essential to operational health, like managing cholesterol in the human body.

- Companies in Sweden and Finland (LKAB 2022) have embraced circular economy principles by recovering metals from tailings and repurposing waste rock for construction materials. Collaborating with local businesses, LKAB created fertilisers from mineral-rich byproducts, reducing waste and generating new revenue streams, mirroring how the human body efficiently re-uses nutrients and energy.

Emerging technologies, such as carbon capture and utilisation (CCU) and blockchain for ESG reporting, further enhance sustainability. CCU transforms emissions into valuable products, while blockchain ensures transparency in sustainability metrics. Together, these innovations align mining practices with systemic health principles, enabling operations to thrive within ecological and social boundaries.

By adopting sustainability as part of a mine's systemic health, mining companies can achieve long-term resilience, balancing economic, environmental and social goals. This approach positions the industry to meet future challenges while contributing to global sustainability objectives.

6 Tailings and water management: lessons from biological systems

The management of tailings and water in mining operations is fundamental to both operational efficiency and environmental responsibility, and it can be effectively understood through the lens of biological systems where interconnected processes maintain balance, detoxify harmful substances and ensure long-term stability. Drawing parallels from biological systems can offer a deeper understanding of how effective waste and water management is crucial for maintaining the long-term health and stability of mining operations. The body's liver, kidneys, and circulatory and digestive systems provide apt analogies for how mining systems must handle detoxification, water balance and the prevention of cascading failures.

In the human body, organs such as the intestines, liver and kidneys play critical roles in filtering toxins, managing fluid balance, and ensuring waste products are safely processed and eliminated. These natural systems are finely tuned to protect the body from systemic harm while recycling nutrients and maintaining equilibrium. Facilities for tailings management act as the intestines (dewatering processes, e.g. thickeners and filters), kidneys and liver (water detoxification processes such as reverse osmosis and ion exchange) for mining operations, filtering and stabilising residual material left after ore processing. TSFs must be designed to safely contain both solid and liquid wastes while preventing the release of harmful substances into the environment.

Much like the body's ability to manage waste and fluid balance under stress, mining operations face the challenge of containing tailings and managing water quality while adapting to complex stressors such as ore variability, climate change and operational risks. As indicated earlier, disruptions in tailings management or water treatment can trigger cascading effects, impacting ecosystems, water quality and even community health.

Tailings often contain a mixture of rock, water and potentially harmful chemicals such as cyanide, heavy metals and residual reagents. Improperly managed tailings can be likened to organ failure, where an overwhelmed or breached system results in catastrophic consequences. Managing these materials is crucial as failures in TSFs have led to devastating environmental and social disasters, such as the Brumadinho and Samarco dam failures in Brazil. When a tailings dam is overloaded or poorly maintained, the consequences can be similarly to how kidney failure affects the body. An overwhelmed filtration system allows harmful substances to accumulate in the bloodstream, leading to widespread health complications. Similarly, when a tailings facility fails, toxins can be released into nearby water bodies, leading to ecosystem damage, soil contamination and harm to downstream communities. Adaptive strategies also consider climate variability, with measures like enhanced drainage systems and vegetation covers helping to stabilise TSFs under extreme weather conditions, reflecting the body's adaptive capacity during stress events.

There are examples of innovative tailings management strategies to mitigate problems. More mines are considering or implementing in-pit disposal, and many mines have adopted paste backfill, where tailings are

mixed with binding agents and used as structural support in underground workings. This reduces the surface tailings storage footprint while enhancing stability, similarly to how the body re-uses essential nutrients while minimising waste accumulation. Co-disposal techniques have been implemented, where tailings and waste rock are combined in a single containment system, reducing the footprint of surface storage while improving physical stability. This approach reflects how the body integrates different waste systems to manage nutrient processing and detoxification simultaneously. There have been pilot tests on electrokinetic dewatering, which uses electrical fields to accelerate water removal from tailings, significantly reducing the volume of saturated waste. This mirrors how the kidneys filter fluids from the bloodstream, managing water balance and toxin removal.

Geotextiles in covers or liners act like cellular barriers, preventing the infiltration of contaminants and helping to stabilise tailings while reducing water infiltration and the risk of leaching harmful substances. In leaching operations, suites of microbial organisms have been applied to break down residual cyanide and stabilise heavy metals. This biomimicry approach resembles the way the body relies on gut microbiota to assist with digestion and toxin breakdown. Bioleaching also has been employed to extract residual copper from its tailings: a biological approach that mirrors the body's enzymatic breakdown of toxins and waste, converting harmful compounds into more stable forms.

Water in mining operations is as vital as blood in the human body. Water management should mirror the circulatory system of the body, where fluids must be distributed efficiently to sustain life while harmful substances are filtered out. In the human body, blood transports nutrients, oxygen and waste while the kidneys filter toxins and maintain fluid balance. Similarly, mining relies on water for ore processing, dust suppression and tailings transport while also requiring effective treatment systems to prevent contamination of surrounding ecosystems. When the body experiences dehydration or fluid overload, the impact can cascade through multiple organ systems, causing strain on the heart, kidneys and brain. Mining faces similar risks when water management systems fail, such as excess rainfall leading to tailings overtopping or insufficient process water causing production inefficiencies.

Much like the bloodstream can become toxic when the liver fails, water exposed to sulphide-bearing minerals can become acidic, leaching heavy metals into nearby ecosystems. Preventative strategies such as alkaline barriers and passive treatment wetlands, like those used in a nickel mine in Indonesia, mimic biological filtration systems by neutralising acidity and absorbing contaminants. Closed-loop systems aim to recycle process water continuously, reducing freshwater withdrawal. However, complete recycling without sufficient treatment can lead to contaminant build-up, similarly to how chronic kidney issues can concentrate toxins. Innovations such as membrane filtration and ion exchange help prevent this issue.

Key challenges for water management include acid mine drainage in which sulphide oxidation can lead to acidic run-off, leaching heavy metals into surrounding water bodies akin to how metabolic imbalances can disrupt the pH balance in the bloodstream. Mining anticipates that climate change impacts could include increasing rainfall variability and droughts that stress water availability and increase tailings fluid volumes, similarly to how the body responds to stress with fluid retention or dehydration. Changes in rainfall patterns and extreme weather events require proactive infrastructure design. Mines often share water resources with local communities and ecosystems. Like the human body prioritising water distribution during dehydration, mining operations in water-scarce regions must balance operational needs with community water access. Overuse of water for industrial purposes can strain relationships with communities, paralleling how nutrient competition in the body affects cellular health.

Relatively recent innovations include the implementation of thickened tailings systems integrated with a water recycling loop, reducing freshwater withdrawal while improving tailings stability. This mirrors how the body conserves water under stress by reabsorbing fluids in the kidneys. Mines have also increasingly used bioremediation and passive treatment wetlands, where natural plant filtration reduced heavy metal concentrations in run-off water. This process resembles how the liver uses enzymes to neutralise toxins and remove them from the bloodstream. Some mines have adopted a zero-liquid discharge system, where process water was entirely recycled, leaving behind solid waste. While highly efficient, this method requires

constant monitoring to prevent mineral build-up, much like how the body must regulate electrolytes to avoid imbalances such as hyperkalaemia. More mines are starting to integrate climate prediction models into their tailings water management systems, incorporating real-time rain forecasting to manage overflow risks. This mirrors how the brain anticipates threats and triggers pre-emptive responses in the body.

Just as the body requires multiple systems working together to ensure overall health, mining operations must integrate tailings management and water treatment strategies holistically. A failure in one area, such as tailings seepage, can impact water quality downstream, while inadequate water recycling can increase tailings volumes and stability risks. Proactive measures, such as real-time monitoring, predictive modelling and collaborative engagement with local communities, can help mitigate these cascading risks.

These lessons from biological systems emphasise the importance of managing tailings and water as interconnected systems where balance, detoxification and stress response are critical. Just as the kidneys and liver work in tandem to filter toxins and manage fluid balance, mining operations must prioritise long-term stability through innovative technologies and climate resilience strategies. By integrating adaptive management practices, biomimicry-based solutions and proactive community engagement, the mining industry can reduce risks, improve operational efficiency and contribute to more sustainable resource management. The whole-system health approach provides a pathway for responsible mining that ensures both operational success and environmental protection.

7 Reprocessing tailings for resource recovery

The analogy of the human body's recycling and waste management systems provides a valuable lens for rethinking about tailings in the mining industry. Just as the body efficiently re-uses nutrients and eliminates waste, mining operations can transform tailings from a waste byproduct and environmental burden into a resource.

Repurposing tailings into building materials is a viable strategy that aligns with the principles of the circular economy. In ecosystems, nothing goes to waste; decomposed plant matter becomes nutrients for new growth. Inspired by this principle, mining companies are exploring ways to repurpose tailings into construction materials, reducing waste and creating new value streams. Tailings can be processed into bricks, paving stones and other building materials, turning a liability into an asset, and benefiting both the company and local communities by providing affordable building materials and economic opportunities in the region. By collaborating with architects, engineers and governments, mining companies can expand the market for tailings-based products. This approach also fosters stronger community relationships as it directly benefits local economies and supports sustainable development goals.

In the human body, nutrients that are not immediately used are stored or recycled for future use. Similarly, mining tailings, which were once considered uneconomical to process, are now being re-examined as a valuable resource. Reprocessing tailings involves extracting residual metals and minerals that were previously overlooked due to technological or economic limitations. This approach not only reduces the volume of waste and mitigates environmental damage but also generates additional revenue. By investing in advanced separation and recovery technologies, companies can not only profit from what was once discarded but also reduce the environmental burden of legacy TSFs. This dual benefit underscores the potential of reprocessing as a cornerstone of sustainable mining practices.

Nature provides remarkable examples of carbon sequestration through mineralisation, such as coral reefs and shellfish forming calcium carbonate structures. These processes stabilise carbon dioxide and contribute to ecosystem stability. Mining companies can draw inspiration from these natural systems to stabilise tailings and sequester carbon, transforming environmental liabilities into assets. For example, several research teams are investigating carbonation by adding specific minerals and catalysts to tailings so that the formation of stable carbonate minerals can be accelerated. The analogy to the human body's systems is clear: just as bones store calcium and provide structural integrity, mineralised tailings can stabilise mine sites while contributing to carbon sequestration goals. This innovative approach positions mining as a potential contributor to global climate solutions.

While the potential for tailings re-use is significant, challenges remain. Tailings often contain hazardous substances, requiring careful management to ensure safety and compliance with environmental regulations. Additionally, the economic feasibility of reprocessing or repurposing tailings depends on the availability of advanced technologies and market demand for derived products. Despite these challenges, the opportunities are vast. By adopting a systemic approach, mining companies can integrate tailings re-use into their overall sustainability strategies. This will require additional investments in research and development, forming partnerships with academic institutions, and engaging with stakeholders to align with objectives including risk mitigation and sustainable practices.

8 Conclusion: mining as a living system

Mining operations, like the human body, thrive when all systems work together in balance. Systemic health depends on the integration of technical efficiency, environmental stewardship and social collaboration. Just as the body's organs, tissues and fluids must operate in harmony to sustain life, mining must consider the long-term stability of its material flow, waste containment, water systems and community relationships.

A mining operation that mirrors the human body must not only focus on maximising resource extraction but also on ensuring systemic resilience. The mining industry faces significant challenges: climate change, increasing ore complexity and rising community expectations. However, these challenges present opportunities for innovation and leadership. Inspired by nature's adaptive processes, mining must:

- Apply integrated geometallurgical thinking from the orebody through to milling operations.
- Integrate planning from exploration through to closure.
- Advance tailings and waste management.
- Rethink water management.
- Build climate-resilient operations.
- Embrace circular economy principles.
- Continue to respond to the demands of the energy transition.
- Strengthen community partnerships.

8.1 Call to action

Mining companies now stand at a turning point. The path forward requires not just incremental improvements, but a fundamental shift toward system-wide health and sustainability. By adopting a holistic, biologically inspired model – where each component supports the stability and resilience of the whole – mining can secure its long-term viability while aligning with global sustainability goals.

This integrated perspective is not merely a metaphor but a functional blueprint for the future of responsible resource extraction. Just as a healthy body relies on proactive care, early detection and balanced resource distribution, mining operations must embrace long-term planning, innovation and collaboration. By doing so, the industry can move beyond extraction alone and become a catalyst for positive environmental restoration, community wellbeing and operational excellence.

The time to act is now. By embracing the lessons of nature, the mining industry can ensure it not only survives but thrives in a world increasingly demanding accountability, equity and sustainability.

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