Yu *et al. Environmental Sciences Europe* (2024) 36:71
https://doi.org/10.1186/s12302-024-00895-9

Environmental Sciences Europe

POLICY BRIEF

Open Access

# Elevating community well-being in mining areas: the proposal of the mining area sustainability index (MASI)

Haoxuan Yu[1,2*], Izni Zahidi[1,2*], Chow Ming Fai[1,2*], Dongfang Liang[3*] and Dag Øivind Madsen[4*]

**Abstract**

In response to the urgent environmental and social challenges posed by mining operations, this paper introduces the Mining Area Sustainability Index (MASI), a novel framework aimed at transforming the mining sector towards sustainable practices. Mining activities have historically led to significant environmental degradation, including water contamination and habitat destruction, contributing to climate change and biodiversity loss. These activities also have profound social implications, such as displacing communities, endangering health, and distributing economic benefits inequitably, often leaving local communities in developing countries marginalized. Recognizing these challenges, this paper outlines the consolidation and standardization in sustainability reporting within the mining sector as a pivotal development. The introduction of international standards by the International Sustainability Standards Board (ISSB) and the European Union's European Sustainability Reporting Standards (ESRS) marks significant strides towards enhancing transparency, accountability, and sustainability across mining operations. Furthermore, the concept of double materiality, assessing both financial and social impacts of mining, represents an advancement in comprehending the broader societal impacts of mining alongside its environmental and economic effects. MASI emerges as a comprehensive tool designed to assess the sustainability of mining areas, offering a nuanced understanding of mining activities' impacts on local environments, societies, and economies. By focusing on localized, community-centric evaluations, MASI aims to fill existing gaps in sustainability assessment and provide a reference for local residents to gauge the sustainability of their surroundings. This framework advocates for a multidimensional approach to sustainability, encompassing ecological preservation, social welfare, and economic viability, urging a reimagined, sustainable future for mining communities.

**Keywords** Sustainable mining, Green technologies, Mining policy

*Correspondence:
Haoxuan Yu
Haoxuan.Yu@monash.edu
Izni Zahidi
Izni.MohdZahidi@monash.edu
Chow Ming Fai
Chow.MingFai@monash.edu
Dongfang Liang
dl359@cam.ac.uk
Dag Øivind Madsen
dag.oivind.madsen@usn.no
[1] Department of Civil Engineering, School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, 47500 Bandar Sunway, Selangor, Malaysia
[2] Monash Climate-Resilient Infrastructure Research Hub (M-CRInfra), School of Engineering, Monash University Malaysia, 47500 Bandar Sunway, Selangor, Malaysia
[3] Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK
[4] Department of Business, Marketing and Law, USN School of Business, University of South-Eastern Norway, Hønefoss, Norway

© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

## Mining's impact: economic growth and sustainability challenges

The mining sector, undeniably a cornerstone of global economic development, has played a pivotal role in shaping the modern world. Its contributions extend far beyond the extraction of minerals and metals. The sector has been instrumental in driving progress across various industries critical to human advancement [1]. The mining sector's critical role in construction, technology, and many other sectors is fundamental to our global infrastructure and technological advancement. The sector provides raw materials essential for infrastructure, including skyscrapers and road networks, and fuels the technological advancements propelling the digital era.

In terms of economic impact, the mining sector is a major contributor to global GDP. It generates significant revenue and creates millions of jobs worldwide, both directly and indirectly [2]. The sector's influence permeates through the entire global economy, impacting various industries through supply chains. Mining operations stimulate growth in ancillary industries, such as transportation, manufacturing, and finance, contributing to economic development worldwide. Furthermore, the sector has been a catalyst for technological innovation, driving advancements in engineering, material sciences, and environmental technologies [3, 4].

However, the impressive contributions of the mining sector to economic growth and technological advancements come with considerable costs, particularly in terms of environmental and social impacts. These impacts necessitate a critical reevaluation of the sector's practices, emphasizing the need for a sustainable approach to mining [5–7].

Historically, mining activities have been closely associated with extensive environmental degradation. The sector's environmental footprint is substantial, with impacts ranging from localized to global scales. One of the most visible impacts of mining is deforestation, which occurs when forests are cleared for mining operations [8, 9]. This deforestation leads to a loss of biodiversity, as forests are home to a large number of species. Soil erosion is another significant impact, which not only degrades the land at the mining site but can also affect surrounding areas through the displacement of soil [10, 11].

Water contamination represents a significant environmental challenge in areas surrounding mining operations. The process of extracting and processing minerals often leads to the release of harmful chemicals into local water bodies, affecting both aquatic life and human populations dependent on these water sources [12]. Furthermore, the mining sector plays a notable role in exacerbating broader global environmental issues, including climate change. It is a significant contributor to climate change, with greenhouse gas emissions resulting from mining activities and associated energy use [13]. Habitat destruction due to mining activities further exacerbates biodiversity loss, disrupting ecological balances and contributing to the global crisis of species extinction.

These environmental challenges are systemic, rooted in the long-standing practices of the mining industry, rather than being isolated incidents. The historical approach to mining has often prioritized economic gain over environmental considerations, leading to long-term ecological damage.

The social ramifications of mining operations are both profound and complex, significantly impacting local communities. Mining operations, particularly in remote and less developed regions, have a significant impact on local communities. One of the most direct effects is the displacement of communities. The establishment of mining operations often requires relocating people, which disrupts their way of life, cultural practices, and social structures. This displacement can lead to a loss of traditional livelihoods and a sense of disconnection from ancestral lands, impacting the social fabric and identity of these communities.

Health risks stemming from mining activities present a substantial challenge to affected communities. Communities near mining sites are often exposed to hazardous substances, including airborne pollutants and chemicals used in the mining process. This exposure can lead to serious health issues, including respiratory problems, waterborne diseases, and other long-term health complications. The health impacts are not limited to physical ailments but also include psychological stress and anxiety resulting from living in close proximity to mining operations [14].

Moreover, while the economic benefits generated by mining are considerable, they are often distributed inequitably. While mining can bring wealth and economic opportunities to a region, it often disproportionately benefits those at the top of the economic ladder. Local communities, particularly in developing countries, may see little of this wealth. This inequity can exacerbate existing social inequalities, leading to tensions and conflicts within communities and between residents and mining companies.

In 2023, the landscape of sustainability reporting within the mining sector began to undergo a significant consolidation, marking a pivotal development in the industry's approach to sustainability. The International Sustainability Standards Board (ISSB) issued its inaugural standards, IFRS S1 and IFRS S2, creating a unified framework for sustainability-related disclosures (https://www.ifrs.org/projects/completed-projects/2023/general-sustainability-related-disclosures/). These standards are designed to enhance transparency and provide a common language for reporting the effects of climate-related risks and opportunities on a company's prospects, incorporating the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD) (https://www.fsb-tcfd.org/). This move towards standardized reporting is further evidenced by the European Union's introduction of the European Sustainability Reporting Standards (ESRS) (https://www.unepfi.org/impact/interoperability/european-sustainability-reporting-standards-esrs), which align with the Global Reporting Initiative (GRI) and IFRS standards, and the collaborative efforts of the International Council of Mining and Metals, the World Gold Council, CopperMark, and the Mining Association of Canada/Towards Sustainable Mining to work under a multi-stakeholder advisory committee towards a globally relevant reporting standard for the mining sector. This initiative reflects the sector's commitment to improving transparency, accountability, and sustainability across its operations.

Furthermore, the introduction of the concept of double materiality, which emphasizes the importance of assessing both the financial and social impacts of mining activities, represents a significant advancement in sustainability reporting. This development responds to growing calls for a more comprehensive understanding of the broader societal impacts of mining, alongside its environmental and economic effects.

These strides towards consolidation and standardization in sustainability reporting within the mining sector highlight an evolving landscape where transparency, accountability, and sustainability are increasingly prioritized. By aligning with global standards such as those set forth by the ISSB and the EU's ESRS, and working collaboratively across various standards organizations, the mining sector is taking critical steps towards ensuring that its contributions to global development are both sustainable and responsible. This alignment not only enhances the sector's sustainability practices but also ensures that it remains a pivotal force in driving global economic development in an environmentally and socially responsible manner.

In this era defined by urgent environmental challenges and heightened social consciousness, the necessity for the mining sector to undergo a transformative shift towards sustainable practices has never been more critical. While existing regulations and standards have primarily focused on the operational aspects of mining, such as the industry's processes and production, a significant gap remains in indicators that delve into the changes within mining areas and communities themselves. These gaps reveal the difficulty in accounting for changes inherent to mining areas, such as environmental conditions, the quality of life in local communities, and economic development initiatives. This observation underscores the need to shift our evaluative focus from a broad (often national or governmental) perspective to a more localized, community-centric viewpoint.

This refined approach calls for the development of an index that not only addresses the macro aspects of sustainability from a governmental or national perspective but also zooms in on the micro, lived experiences of people in mining communities. Such an index would serve as a critical tool in assessing the sustainability of mining areas, providing local residents with a reference for understanding the impact of mining on their environment, livelihoods, and economic development. By transitioning our focus to the grassroots level, we can begin to formulate indicators that truly reflect the multifaceted impacts of mining operations, thereby contributing to a more sustainable future for mining communities.

To bridge this gap, we introduce a pioneering conceptual framework: the Mining Area Sustainability Index (MASI). MASI is envisioned to serve as a comprehensive tool to assess the sustainability of mining areas, offering a nuanced understanding of how mining activities impact local environments, societies, and economies. This proposed index aims not only to fill the existing void in mining sustainability assessment but also to provide local residents with a tangible reference point to gauge the sustainability of their surroundings.

Our advocacy for MASI represents a call to action for a collective reimagining of mining practices. By adopting a multidimensional approach, MASI seeks to encapsulate a broad spectrum of sustainability metrics—ranging from ecological preservation and social welfare to economic viability. This shift towards a more integrated assessment framework promises to redefine the mining sector's approach to sustainability, ensuring that it aligns more closely with the needs and well-being of local communities.

The development and implementation of MASI require a collaborative effort among academics, industry professionals, policymakers, and the communities directly affected by mining activities. It invites a broader discourse on sustainability within the mining sector, encouraging a participatory approach in crafting solutions that are both pragmatic and inclusive. As proponents of this initiative, we envision MASI as a catalyst for fundamental changes in mining practices, steering the sector towards a future where economic development does not come at the expense of environmental integrity and social equity.

In conclusion, while the mining sector has traditionally been a bedrock of global economic development, the time has come for a paradigm shift towards sustainability that prioritizes the health of our planet and its inhabitants. Through the introduction of MASI, we lay down a foundational framework for evaluating and enhancing the sustainability of mining areas. This endeavor is not just about mitigating the adverse effects of mining but about fostering a sector that contributes positively to the sustainable development of mining communities and beyond.

## Sustainable mining future: conceptualizing the mining area sustainability index (MASI)

In an era defined by pressing environmental challenges and heightened social consciousness, the mining industry faces an urgent need to transform towards sustainable practices. As mentioned in the introduction, the majority of current regulations and metrics focus on the macro aspects of the mining industry itself or production processes. There is a noticeable void in standards, policies, and metrics that delve into mining areas, examining the lives of the residents within these communities. To address this gap, we propose a conceptual framework—the Mining Area Sustainability Index (MASI)—aimed at steering the mining industry towards a more sustainable future. This paper aims to outline the potential components of MASI, providing a foundation for further research and discussion among academics, industry professionals, and the broader public. As advocates of this concept, we suggest a multidimensional approach that has the potential to fundamentally reshape mining practices (as illustrated in Fig. 1).

Expanding on this, it is crucial to understand that sustainable mining practices require a shift in focus from solely economic or production metrics to include environmental stewardship and social well-being. The proposed MASI framework seeks to fill the existing gap by integrating comprehensive assessments of environmental impact, community engagement, economic benefits distribution, and long-term ecological and social sustainability into the evaluation of mining operations. By adopting such an approach, the mining industry can move beyond traditional metrics of success and embrace a more holistic view of sustainability that encompasses not just the economic output but also the welfare of local communities and the preservation of the environment. This multidimensional perspective on mining practices acknowledges the interconnectedness of environmental health, social equity, and economic viability, offering a path forward that aligns with the global push towards sustainability and responsible resource management.

To delve deeper into the sustainability factors within mining areas, it is essential first to identify and address which indicators are crucial in the social, economic, and environmental aspects of sustainability in these areas. Accordingly, we have formulated nine assessment indicators/criterions (C1–C9), where C1–C3 are economic indicators, primarily aimed at evaluating the extent of economic impact caused by mining and related developments within the mining area. C4–C6 are social indicators, focusing on assessing the impact of mining and related developments on the welfare of the people, as

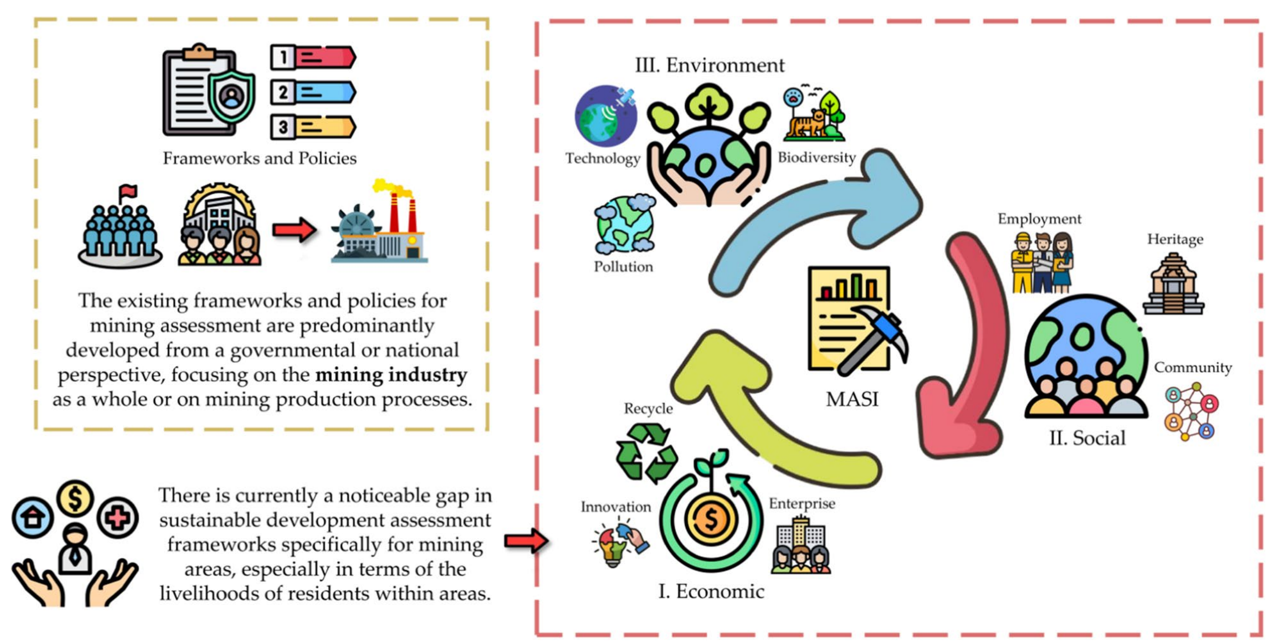


**Fig. 1** Synergies of Sustainability: The MASI Framework's Triadic Aspect to Mining

well as the protection and promotion of culture within the area. Lastly, C7–C9 are environmental indicators, intended to evaluate the potential environmental degradation or restoration resulting from mining and related development and recovery activities in the area.

### Economic dimension: potential components

Local Economic Impact (C1). The proposed economic dimension of the Mining Area Sustainability Index (MASI) begins with the assessment of local economic impact. This involves measuring how mining activities contribute to local economies, focusing on job creation and the support for local businesses [15]. MASI aims to quantify not only the number of jobs generated but also their quality, including aspects like stability, wages, and growth opportunities. Additionally, the framework considers the support mining companies provide to local businesses, evaluating how they integrate with and bolster local supply chains and services. This approach recognizes the importance of mining operations in stimulating local economic development and aims to ensure these benefits are both substantial and sustainable.

Regarding indicator C1, the economic benefits brought by mining companies within the mining area are undoubtedly a key factor to consider. If a mining area hosts a large mining company that can drive local economic prosperity and development, and create employment opportunities for local residents, it would significantly contribute positively to this indicator. Additionally, the potential opportunities for local suppliers and service providers that come with mining operations should also be taken into account. For example, if a mine opts for the backfill mining method for ore recovery, this could spur the development of local cement manufacturers. Similarly, if a mine reclaims its abandoned mine land for agricultural use [2], it could boost local agricultural development and the sales of agricultural products.

Resource Efficiency (C2) is a potential component under the economic dimension of MASI. This aspect assesses how effectively natural resources are utilized and conserved during mining operations. It involves evaluating the efficiency of resource extraction processes and the implementation of practices that minimize waste and maximize the use of extracted materials. The framework also considers the adoption of recycling and reuse practices within mining operations. By focusing on resource efficiency, MASI encourages mining companies to adopt more sustainable practices that not only optimize resource use but also reduce environmental impacts, aligning economic activities with principles of sustainability [16, 17].

For indicator C2, the efficiency of resource extraction is closely related to the mining method employed. For instance, the backfill mining method represents an efficient and environmentally friendly approach to ore recovery and stabilizing underground environments. Additionally, employing the backfill mining method means that waste materials generated during the mining process are recycled back into the operation, embodying the principles of a circular economy. Therefore, the use of backfill mining method undoubtedly scores positively in the C2 category.

Economic Sustainability (C3) involves the evaluation of the long-term economic viability of mining activities. This component extends the focus beyond immediate financial returns to consider the broader, long-term economic implications of mining operations, including their impact on future generations [18]. It entails an assessment of how mining activities contribute to or detract from sustainable economic growth within the regions they operate. This includes analyzing the balance between immediate economic gains and the potential for future environmental and social costs. The aim is to promote mining practices that are economically beneficial in the short term while ensuring they do not compromise the ecological and social foundations necessary for long-term economic health and stability [19].

Regarding indicator C3, adopting a long-term economic development model is essential. For example, the Sungai Lembing mining area in Malaysia transformed into a green tourism city after its mines were depleted, laying a foundation for its long-term economic development and yielding significant environmental benefits [20]. Furthermore, actively incorporating ore dressing plants and smelters to extend from ore extraction to more extensive resource processing and smelting could also earn additional points in this indicator.

### Social dimension: proposed areas of focus

Community Engagement and Impact (C4). A pivotal area in the social dimension of the Mining Area Sustainability Index (MASI) is the assessment of community engagement and impact. This aspect involves a thorough evaluation of how mining companies interact and integrate with local communities. It includes measuring the effectiveness of their communication strategies, the extent of their involvement in community development projects, and their responsiveness to community concerns and needs. MASI aims to quantify the impact of mining activities on local populations, assessing both positive contributions and potential negative repercussions. This evaluation is particularly focused on the mining companies' efforts in conducting thorough impact assessments and their strategies for conflict resolution. By emphasizing community engagement and impact, MASI encourages mining operations to foster positive relationships with local communities, ensuring that their activities are conducted in a way that is not only socially responsible but also beneficial to the community's overall well-being [21, 22].

For indicator C4, the resonance of mining and development activities within the community and their ability to improve residents' lives is a crucial aspect. For instance, the establishment of mining companies that lead to the development of mining communities, including the construction of worker dormitories, family residential areas, cinemas, and recreational facilities, has a positive impact that should be recognized and encouraged.

Worker Rights and Safety (C5). Worker rights and safety form another crucial component of MASI's social dimension. This facet involves a detailed evaluation of labor practices within mining companies, with a focus on ensuring the safety, rights, and fair compensation of all workers [23]. MASI proposes to assess the conditions under which mining employees work, including safety protocols, health risks, and protective measures in place. The framework also examines issues related to fair wages, equitable treatment, and opportunities for career advancement [24]. By including worker rights and safety in its assessment criteria, MASI aims to promote a mining industry that not only adheres to the highest standards of labor practices but also champions the rights and well-being of its workforce.

For indicator C5, the treatment and welfare of workers are undoubtedly important, but their safety is paramount. This is also somewhat related to the mining method employed. Without a doubt, the backfill mining method, which supports the surrounding rock while recovering ore, thus stabilizing the underground environment, can ensure the safety of workers during underground operations. Additionally, the health protection of workers is crucial, such as the availability of dust control facilities to prevent occupational diseases among workers.

Cultural and Heritage Preservation (C6). The preservation of cultural and heritage sites is an integral part of the social dimension of MASI. This component focuses on how mining operations impact local cultural practices and significant heritage sites [25]. MASI aims to assess the measures taken by mining companies to protect and preserve these sites and practices, considering the cultural significance and value they hold for local communities. This includes evaluating the extent to which mining activities are planned and executed in a manner that avoids damage to cultural heritage and, where necessary, involves strategies for the restoration and preservation of such sites. The inclusion of cultural and heritage preservation in MASI highlights the importance of respecting and safeguarding cultural identities and histories, promoting mining practices that are not only economically and environmentally sustainable but also culturally sensitive and responsible.

For indicator C6, mining activities should be contained within a scope that allows for the control of their environmental disturbances, aiming to minimize the expansion of development activities that necessitate relocations and the destruction of local culture and heritage. Additionally, the preservation of the natural scenery in mining areas falls within this scope. Malaysia's Sungai Lembing serves as an excellent example, demonstrating that while some degree of resource development has occurred, the majority of the original residential culture, heritage, and natural landscapes have been preserved [20].

### Environmental dimension: challenges and proposed indicators

Biodiversity Impact (C7). One of the key components of the environmental dimension is the assessment of biodiversity impact. This includes evaluating the effects of mining activities on local ecosystems, particularly in terms of habitat destruction and the consequent impact on biodiversity. The MASI framework aims to quantify how mining operations affect local flora and fauna, considering both the direct impact of habitat loss and the indirect effects such as fragmentation of ecosystems [26, 27]. It also involves assessing the efforts made by mining companies to conserve species and rehabilitate habitats. This component underscores the importance of protecting biodiversity as an integral part of environmental sustainability in mining.

Regarding indicator C7, the impact on biodiversity often traces back to the destruction and protection of animal habitats, along with other factors that influence the complex balance of local ecosystems. For instance, if a mining area has implemented successful afforestation efforts, it can be considered to have a positive impact on biodiversity, warranting a high score.

Waste Management (C8). Another critical aspect under the environmental dimension is the evaluation of pollution control and waste management practices. This involves assessing how effectively mining operations manage their emissions, discharges, and waste products to minimize environmental pollution. The MASI framework proposes to scrutinize the methods and technologies employed by mining companies to treat and dispose of waste, including measures to prevent soil, water, and air pollution [28]. By focusing on pollution and waste management, MASI encourages mining operations to adopt cleaner and more responsible practices that reduce their environmental footprint [29].

Regarding indicator C8, waste disposal represents one of the most significant environmental impacts within the mining process, thus meriting particular emphasis. Key considerations for scoring in this area include whether tailings are being isolated, whether the backfill mining method is employed to recycle mining waste, and whether there is an encouragement to repurpose mining waste as raw materials for other products. These practices are essential in mitigating the environmental impact of waste generated from mining operations.

Comprehensive ecological and environmental surveys are a cornerstone in understanding the impacts of mining activities. However, these processes are notably time consuming and resource intensive [30]. Given these challenges, there is an urgent need for more streamlined, integrated environmental assessment technologies. An ideal solution would be a method that can visually and intuitively express habitat reduction or restoration, as well as mining destruction or reclamation, while also being convenient and providing immediate information for relevant stakeholders. Such a development would be a boon to our world, offering a more efficient and effective way to monitor and assess the environmental impacts of mining.

In light of this, our attention turns towards satellite remote sensing technology [31, 32]. Satellite data have the potential to provide timely and rich information about the environmental changes caused by mining. This technology can revolutionize how we monitor ecological changes, offering a bird's-eye view of the impacts on landscapes and ecosystems.

Satellite remote sensing offers several advantages. Firstly, it provides a comprehensive overview of large and inaccessible areas, which is often challenging with ground-based surveys. Secondly, it offers the ability to track changes over time, providing a dynamic understanding of how mining activities impact the environment. These longitudinal data are invaluable in assessing the effectiveness of restoration efforts and in planning future conservation strategies.

Furthermore, advancements in satellite technology mean that the data obtained are increasingly detailed and accurate. Innovations in imaging technologies enable the detection of subtle changes in vegetation cover, water quality, and land use patterns. This level of detail is crucial in understanding the nuanced impacts of mining and in developing targeted mitigation strategies.

Looking ahead, the integration of satellite remote sensing with other emerging technologies, such as artificial intelligence and machine learning, could further enhance our capabilities [33]. These technologies can process vast amounts of satellite data, identifying patterns and trends that might be missed by the human eye. They can also predict potential future impacts, aiding in proactive decision-making.

There is a growing trend towards using remote sensing technology to calculate vegetation cover in mining areas. This approach allows for the inference of environmental changes based on variations in vegetation cover. This is because there is a direct correlation between the expansion of mining activities and the reduction of vegetation cover, while environmental restoration efforts, such as afforestation, directly contribute to an increase in vegetation cover. Therefore, in the last indicator, Vegetation Cover is set as C9. For C9, if a mining area's vegetation cover remains stable or increases over time, it indicates stable environmental conditions and should be awarded a high score, and vice versa.

#### MASI: proposal for constructing a mathematical model

Currently, we are exploring the use of various mathematical models to develop a scoring system for assessing the sustainability of mining areas through the Mining Area Sustainability Index (MASI). Methods such as the widely recognized Analytic Hierarchy Process (AHP) rely on expert evaluations to assess the sustainability of mining areas. Based on these expert evaluations, we compute the sustainability of different mining areas and, through case studies, gather insights to establish a standardized scoring system tailored to the specific characteristics of mining areas. Once established, this system will eliminate the reliance on expert evaluations, allowing for the sustainability of mining areas to be assessed through this standardized scoring system.

For example, we plan to adopt the Pythagorean fuzzy set and integrate it with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method to construct the MASI scoring system. Here is an illustration: initially, we conduct case studies on various mining areas based on expert assessments using this decision-making approach. This method aids us in accumulating experience and establishing a standardized scoring system. Background information, conceptual frameworks, and the preliminary process of constructing the evaluation system are all detailed in the supplementary document section. Please refer to the Supplementary Document for our explanations.

In summary, the logic of our plan is to initially employ decision-making methodologies, such as the Analytic Hierarchy Process (AHP), Key Matrix Method, Fuzzy Comprehensive Evaluation, PFS-TOPSIS, etc., to construct an evaluation system for mining areas C1-C9. This phase primarily relies on expert scoring, whereby through the perspectives of experts, a subset of mining areas are subjected to case analysis and scoring. As demonstrated in Additional file 1: Fig. S1A, experts assign scores to each mining area on every indicator, ranging from perfect to very poor, rating the performance on each criterion for every assessed mining area. Each score is then converted into a Pythagorean Fuzzy Number (PFN) for further calculation, ultimately yielding a final score. By summarizing the opinions of experts, we can establish a standardized scoring framework that allows for the scoring of other mining areas without relying on expert scoring. As illustrated in Additional file 1: Fig. S1B, we propose a simplified example: if experts typically score based on the strengths and weaknesses reflected by each mining area in each indicator (C), adding a point for strengths and deducting a point for weaknesses, with scores from -4 to 4 corresponding, respectively, from Very very bad to perfect; then in this manner, we can establish a standardized scoring framework based on the performance strengths and weaknesses in each criterion, allowing for the scoring of new mining areas. Scores can be directly assigned based on their strengths and weaknesses in each criterion, and through complex calculations, their scores can be derived.

Indeed, this represents merely one concept or proposition based on the "Policy Brief" paper itself. Other methodologies might also hold potential for application in the development of the Mining Area Sustainability Index (MASI), including the previously mentioned Analytic Hierarchy Process (AHP), correlation matrix methods, and even some advanced machine learning techniques. Regardless of the method employed, it is likely that the process will encompass some of the steps we have envisioned. Hence, our proposal could offer reference points and inspiration for other researchers. Furthermore, we are committed to the ongoing development and evaluation of MASI, conducting multiple case studies, and gathering relevant insights to ultimately establish a standardized framework for assessing the sustainability of mining areas.

## Discussion

### The potential role and impact of MASI in sustainable mining practices

The comparison between MASI and existing sustainability indices and frameworks in the mining industry underscores the distinct approach and potential impact of MASI (as shown in Table 1). Unlike broader frameworks like GRI (Global Reporting Index) [34] and DJSI (Dow Jones Sustainability Indices) [35], MASI is specifically tailored to address the unique challenges of the mining sector. Its comprehensive, multidimensional framework integrates economic viability, social responsibility, and environmental stewardship, offering a holistic approach to sustainability in mining.

MASI's emphasis on local community involvement sets it apart from other frameworks. This aspect is crucial as it ensures that the voices and concerns of those most affected by mining activities are heard and addressed. By incorporating local perspectives, MASI promotes a more inclusive and socially responsible approach to mining.

Furthermore, MASI's practical focus on operational sustainability makes it a valuable tool for the mining industry. Unlike the MPF (Mining Policy Framework) [36, 37] and MSAT (Mine Site Assessment Tool) [38, 39], which are policy-oriented, and investor-focused indices like DJSI, MASI provides a framework for assessing and improving sustainability at the operational level. This hands-on approach is essential for driving real change in mining practices.

The implementation (if) of MASI could provide a significant leap forward in sustainable mining. By building on the strengths of existing frameworks and addressing their limitations, MASI has the potential to become a leading standard for sustainability in the mining industry. Its success, however, will depend on the active engagement and collaboration of all stakeholders, including policymakers, industry professionals, researchers, and community representatives.

In addition to the global standards previously mentioned, there are several pivotal regulations, policies, and frameworks within the mining industry that are essential to highlight. Among these, the Initiative for Responsible Mining Assurance (IRMA) stands out for providing a comprehensive standard for responsible mining [40]. It emphasizes ethical practices, labor rights, human rights, health and safety, and environmental management. IRMA shares similarities with the Mining Area Sustainability Index (MASI) in considering the health, safety, and environmental management of mining areas. However, IRMA and MASI differ in their approaches: IRMA presents a unique and holistic assessment standard, governed equally by the private sector, local communities, civil society, and workers, making it a true multi-stakeholder initiative. In contrast, MASI offers a more community-focused assessment of mining areas, prioritizing the socio-economic environment of the area, especially the living standards of the local population.

Similarly, the Towards Sustainable Mining (TSM) initiative [41, 42], like IRMA, provides a comprehensive assessment framework, built around nine protocols with 34 indicators covering various aspects of social and environmental performance. The second advantage of MASI over both TSM and IRMA lies in the simplicity and accessibility of its assessment results. By making the evaluation outcomes understandable to the local population, MASI empowers residents with knowledge of their living conditions, enabling them to advocate for and implement necessary changes.

It is anticipated that in the future, each standard will play a distinct role in collectively safeguarding the

**Table 1** Comparative analysis of mining sustainability frameworks: MASI in context

| Aspect | MASI | Global Reporting Index (GRI) | Dow Jones Sustainability Indices (DJSI) | Mining Policy Framework (MPF) | Mine Site Assessment Tool (MSAT) |
|---|---|---|---|---|---|
| Focus | Comprehensive framework for sustainable mining, integrating economic, social, environmental aspects | Quantifies sustainability from academic literature and reporting frameworks | Tracks stock performance of companies in terms of economic, environmental, and social criteria | Best practices for environmental, social, and economic governance in mining | Practical tool for stakeholder engagement on sustainability issues at mine sites |
| Scope | Specific to mining operations | Broad, includes various companies | Broad, across 61 industries including mining | Broad, supports over 80 member countries in sustainable mining development | Specific to individual mine sites |
| Key Features | Holistic, multidimensional approach; local community involvement | Focus on sustainability reporting and indicators | Investor-focused, benchmarks for sustainable business practices | Policy and governance focused, outlines best practices for the entire mining sector | Dialogue and assessment tool for local stakeholders to engage with mining companies |
| Implementation | Proposed, inviting stakeholder contributions | Used for sustainability reporting in various industries | Implemented, serves as a benchmark for investors | Ratified and recognized by the United Nations Commission on Sustainable Development, focuses on systemic approach to mining in line with sustainable development principles | Implemented, designed for constructive engagement at any mine site |
| Stakeholder Engagement | Broad, including researchers, policymakers, industry professionals, community representatives | Varied, depending on company reporting | Investors, companies across industries | Member countries, policymakers, industry professionals | Local communities, civil society, workers, trade unions, local government |
| Sustainability Dimensions Addressed | Economic viability, social responsibility, environmental stewardship | Depends on company reporting | Economic, environmental, social criteria | Environmental, social, economic governance, financial benefits, socio-economic benefits, environmental management, post-mining transition, artisanal and small-scale mining | Focuses on fundamental issues affecting mine sites and their neighbors |

sustainable development of the world's mining industry. The Mining Area Sustainability Index (MASI), with its heightened focus on and proximity to the lives of residents, offers a unique perspective on sustainable mining practices. MASI stands out by directly engaging with community-level concerns, emphasizing the socio-economic and environmental impacts of mining operations on local populations. This approach not only highlights the immediate effects of mining activities but also fosters a deeper understanding among local communities about how these operations can be managed in a more sustainable and responsible manner.

By prioritizing the well-being and living standards of the communities affected by mining, MASI encourages a more inclusive and participatory approach to sustainability in the mining sector. This involves not only assessing but actively improving the quality of life for those living in mining areas, ensuring that the benefits of mining are equitably shared and that adverse impacts are minimized. In doing so, MASI contributes to a broader goal of sustainable development that integrates economic growth with environmental stewardship and social justice.

As MASI and other standards like IRMA and TSM continue to evolve, their collective impact could lead to significant advancements in sustainable mining practices worldwide. Each framework, with its unique focus and methodology, complements the others in striving for a mining industry that is not only profitable but also responsible, ethical, and harmonious with the needs of the planet and its people. The future of mining sustainability lies in the collaboration and mutual reinforcement of these standards, each contributing to a holistic approach that balances the demands of industry with the imperative of sustainability.

## Envisioning a collaborative framework for sustainable mining

The concept of the Mining and Sustainability Initiative (MASI) represents a forward-thinking vision, aimed at revolutionizing the mining sector through sustainable practices. At this stage, MASI is a proposal, an aspirational blueprint that invites an extensive and varied group of stakeholders to contribute towards its development and eventual realization.

At the heart of MASI lies the principle of collaborative engagement, inviting a spectrum of contributors from various sectors to participate actively in shaping the future of mining. Researchers play a pivotal role in this consortium, tasked with infusing the initiative with scientific rigor and cutting-edge innovations. Their contributions are critical in identifying and developing technologies and methodologies that significantly reduce the environmental footprint of mining activities. By employing an interdisciplinary approach that blends environmental science, social sciences, and engineering, researchers can formulate holistic strategies that address the complex challenges of mining, ensuring that sustainability is not just a concept but a practical reality [43].

Policymakers are another crucial pillar within the MASI framework, responsible for creating a conducive legal and regulatory landscape that nurtures sustainable mining practices [36]. Their work involves the translation of the collaborative dialogue into tangible policies and frameworks that not only encourage but also, in certain instances, mandate adherence to sustainable practices. This legislative backbone is essential for establishing a standardized approach to sustainable mining, ensuring that the industry operates within parameters that safeguard environmental health and social well-being.

Industry professionals, the linchpins of mining operations, bring invaluable practical insights to the table. Their day-to-day experiences and operational knowledge are indispensable for testing the feasibility and effectiveness of proposed sustainability measures. Ensuring that these measures are not merely theoretical constructs but are also viable in the real-world context of mining operations is essential for the successful implementation of MASI's principles.

Community representatives stand as the voice of those directly impacted by mining activities. Their involvement guarantees that MASI remains grounded in the realities and concerns of local communities, particularly regarding environmental degradation and social disruption. This participatory approach ensures that the initiative is not only about mitigating negative impacts but also about enhancing the positive contributions of mining to community development and well-being [44].

MASI envisions a future where sustainable mining is not an optional practice but a fundamental aspect of the industry. This vision includes developing a continuously evolving framework that is responsive to new challenges and opportunities, guided by the principles of adaptability and innovation. It calls for a paradigm shift in how mining is perceived and practiced, emphasizing the need for a balance between extracting valuable resources and preserving the planet for future generations.

The initiative's success hinges on the collective effort and commitment of all stakeholders involved. By fostering an environment of open dialogue, shared goals, and mutual respect, MASI aims to build a consensus on the importance of sustainability in mining. It seeks to demonstrate that through collaboration, innovation, and dedication, it is possible to transform the mining sector into a model of sustainable development that contributes positively to the global economy, society, and the environment.

In sum, the Mining and Sustainability Initiative (MASI) represents a bold and ambitious endeavor to reimagine the mining industry through the lens of sustainability. By harnessing the collective expertise, experiences, and energies of a diverse group of stakeholders, MASI aims to chart a new course for mining—one that is sustainable, responsible, and beneficial to all. The journey towards achieving this vision will undoubtedly be complex and challenging, but with perseverance and collaboration, it is a goal within reach, promising a future where mining and sustainability go hand in hand.

## Conclusion

This study presents the Mining Area Sustainability Index (MASI), a pioneering framework designed to assess and enhance sustainability practices within the mining industry. By integrating economic, social, and environmental dimensions, MASI offers a holistic approach to sustainability, addressing the critical need for a balance between resource extraction and the well-being of ecosystems and communities:

- Economic Viability: Our findings underscore the importance of economic viability as a cornerstone of sustainable mining. MASI facilitates the identification of practices that not only ensure the long-term profitability of mining operations but also promote economic development within local communities. This dual focus on the economic aspects of sustainability encourages the industry to adopt strategies that yield both financial and social benefits.
- Social Responsibility: The social dimension of MASI emphasizes the mining industry's responsibility towards the communities within which it operates. By incorporating social indicators into the sustainability assessment, MASI encourages practices that respect human rights, promote fair labor conditions, and foster community engagement and development. This approach highlights the essential role of social equity and justice in achieving sustainability in mining activities.
- Environmental Stewardship: Environmental stewardship is another critical component of MASI, reflecting the urgent need to minimize the ecological footprint of mining operations. Our research demonstrates how MASI's environmental criteria help identify and implement practices that protect biodiversity, conserve water resources, and reduce pollution and waste. This commitment to environmental preservation is crucial for ensuring the sector's sustainability and resilience against the challenges posed by climate change.
- Future Directions: Looking forward, MASI provides a solid foundation for advancing sustainability in the mining sector. It encourages ongoing research to refine sustainability indicators and adapt them to evolving environmental and societal needs. Additionally, MASI's framework fosters collaboration among stakeholders, including mining companies, governments, communities, and environmental organizations, to promote best practices and drive positive change.

In conclusion, the introduction of the Mining Area Sustainability Index represents a significant step towards sustainable mining. By addressing economic, social, and environmental dimensions comprehensively, MASI not only guides the mining industry towards more responsible practices but also contributes to the global sustainability agenda. As the industry continues to evolve, MASI's adaptable and inclusive framework will be instrumental in shaping a future where mining activities are in harmony with the planet and its inhabitants.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-024-00895-9.

**Additional file 1.** PFS-TOPSIS method for MASI (a simple example). **Figure S1. A** Example: calculation of expert scores for hypothetical mining areas A1–A4; **B** Example: Summarizing expert insights to construct a standardized scoring framework.

**Acknowledgements**

H.Y. thanks the Graduate Research Excellence Scholarship (GRES) from Monash University Malaysia, and D.Ø.M. thanks the publication supporting by University of South-Eastern Norway. *Image Sources*—All graphic elements utilized in Figure 1 are sourced from flaticon.com and freepik.com. They are free to use and not subject to copyright restrictions. The author, Haoxuan Yu, is a premium member of both websites (account: @user81357068), and hence, attribution is not required for the materials used.

**Author contributions**

H.Y. and I.Z. contributed to conceptualization; H.Y. performed methodology, formal analysis, data curation, visualization, and writing—original draft preparation and provided resources; I.Z. and D.L. did validation; H.Y., I.Z., C.M.F., D.L., and D.Ø.M. were involved in writing—review and editing; I.Z., C.M.F., and D.L. did supervision; I.Z performed project administration. All authors have read and agreed to the published version of the manuscript. All authors are listed as corresponding authors due to their equally significant contributions in a specific field.

**Funding**

Open access funding provided by University Of South-Eastern Norway. H.Y. thanks the Graduate Research Excellence Scholarship (GRES) from Monash University Malaysia, and D.Ø.M. thanks the publication supporting by University of South-Eastern Norway.

**Availability of data and materials**

Not applicable.

## Declarations

### Ethics approval and consent to participate
Not applicable.

### Competing interests
The authors declare no competing interests.

Received: 19 December 2023 Accepted: 24 March 2024
Published online: 04 April 2024

### References
1. Hodge RA, Ericsson M, Löf O, Löf A, Semkowich P (2022) The global mining industry: corporate profile, complexity, and change. Miner Econ 35(3–4):587–606
2. Yu H, Zahidi I, Fai CM (2023) Reclaiming abandoned mine tailings ponds for agricultural use: Opportunities and challenges. Environ Res 232:116336
3. Li S, Zhang R, Feng R, Hu B, Wang G, Yu H (2021) Feasibility of recycling Bayer process red mud for the safety backfill mining of layered soft bauxite under coal seams. Minerals 11(7):722
4. Li S, Zhang Y, Feng R, Yu H, Pan J, Bian J (2021) Environmental safety analysis of red mud-based cemented backfill on groundwater. Int J Environ Res Public Health 18(15):8094
5. Yu H, Li S, Wang X (2022) The recent progress China has made in the backfill mining method, part III: Practical engineering problems in stope and goaf backfill. Minerals 12(1):88
6. Li S, Yu Z, Yu H, Wang X (2022) The recent progress china has made in high-concentration backfill. Sustainability 14(5):2758
7. Yu H, Li S, Yu L, Wang X (2022) The recent progress China has made in green mine construction, part II: typical examples of green mines. Int J Environ Res Public Health 19(13):8166
8. Yu H, Zahidi I (2023) Spatial and temporal variation of vegetation cover in the main mining area of Qibaoshan Town, China: Potential impacts from mining damage, solid waste discharge and land reclamation. Sci Total Environ 859:160392
9. Yu H, Zahidi I, Liang D (2023) Mine land reclamation, mine land reuse, and vegetation cover change: an intriguing case study in Dartford, the United Kingdom. Environ Res 225:115613
10. Yu H, Zahidi I, Liang D (2023) Spatiotemporal variation of vegetation cover in mining areas of Dexing City, China. Environ Res 225:115634
11. Yu H, Zahidi I, Chow MF (2023) Vegetation as an ecological indicator in assessing environmental restoration in mining areas. Iscience 26(9):107667
12. Li S, Yu L, Jiang W, Yu H, Wang X (2022) The recent progress China has made in green mine construction, Part I: mining groundwater pollution and sustainable mining. Int J Environ Res Public Health 19(9):5673
13. Odell SD, Bebbington A, Frey KE (2018) Mining and climate change: a review and framework for analysis. Extr Ind Soc 5(1):201–214
14. Yu H, Zahidi I (2023) Environmental hazards posed by mine dust, and monitoring method of mine dust pollution using remote sensing technologies: an overview. Sci Total Environ 864:161135
15. Moritz T, Ejdemo T, Söderholm P, Wårell L (2017) The local employment impacts of mining: an econometric analysis of job multipliers in northern Sweden. Miner Econ 30:53–65
16. Bender AP, Bilotta P (2020) Circular economy and urban mining: resource efficiency in the construction sector for sustainable cities. Sustain Cities Commun. https://doi.org/10.1007/978-3-319-95717-3_40
17. Jandieri G (2023) Increasing the efficiency of secondary resources in the mining and metallurgical industry. J South Afr Inst Min Metall 123(1):1–8
18. Jovanović V, Stanković S, Krstić V (2023) Environmental, social and economic sustainability in mining companies as a result of the interaction between knowledge management and green innovation—the SEM approach. Sustainability 15(16):12122
19. Cole MJ, Broadhurst JL (2022) Sustainable development in mining communities: the case of South Africa's West Wits Goldfield. Front Sustain Cities 4:87
20. Yu H, Gunaratna G, Zahidi I, Fai CM (2024) Sungai Lembing's green tourism: pioneering the future of resource-based urban renewal. Innovation 5:100578
21. Prno J, Pickard M, Kaiyogana J (2021) Effective community engagement during the environmental assessment of a mining project in the canadian arctic. Environ Manag 67(5):1000–1015
22. Mwakesi I, Wahome R, Ichang'i D (2020) Mining impact on communities' livelihoods: a case study of Taita Taveta County, Kenya. AIMS Environ Sci 7(3):286–302
23. Yang L, Birhane GE, Zhu J, Geng J (2021) Mining employees safety and the application of information technology in coal mining. Front Public Health 9:709987
24. Tripathy DP, Parida S, Khandu L (2021) Safety risk assessment and risk prediction in underground coal mines using machine learning techniques. J Inst Eng Ser D 102(2):495–504
25. Bertolin C (2019) Preservation of cultural heritage and resources threatened by climate change. Geosciences 9(6):250
26. Kruger E, Pohlo R (2022) Analysis of biodiversity impacts in mining environmental impact assessments before and after 2013 from Mpumalanga province, South Africa. Environ Monitor Assess 194(7):521
27. Katona S, Paulikas D, Ali S, Clarke M, Ilves E, Lovejoy TE, Stone GS (2023) Land and deep-sea mining: the challenges of comparing biodiversity impacts. Biodivers Conserv 32(4):1125–1164
28. Shengo LM (2021) Review of practices in the managements of mineral wastes: the case of waste rocks and mine tailings. Water Air Soil Pollut 232(7):273
29. Yu H, Zahidi I, Liang D (2023) Sustainable porous-insulation concrete (SPIC) material: recycling aggregates from mine solid waste, white waste and construction waste. J Market Res 23:5733–5745
30. Han X, Cao T, Yan X (2021) Comprehensive evaluation of ecological environment quality of mining area based on sustainable development indicators: a case study of Yanzhou Mining in China. Environ Dev Sustain 23:7581–7605
31. Zhu D, Chen T, Zhen N, Niu R (2020) Monitoring the effects of open-pit mining on the eco-environment using a moving window-based remote sensing ecological index. Environ Sci Pollut Res 27:15716–15728
32. Roy PS, Behera MD, Srivastav SK (2017) Satellite remote sensing: sensors, applications and techniques. Proc Natl Acad Sci, India, Sect A 87:465–472
33. Jung D, Choi Y (2021) Systematic review of machine learning applications in mining: exploration, exploitation, and reclamation. Minerals 11(2):148
34. Perez F, Sanchez LE (2009) Assessing the evolution of sustainability reporting in the mining sector. Environ Manag 43:949–961
35. Torinelli VH, Junior AFDADS, Souza ALRD, Gomes SMDS, Andrade JCS (2020) The impacts of environmental disasters on share value and sustainability index: an analysis of Vale company facing Mariana and Brumadinho disasters-Brazil. Latin Am J Manag Sustain Dev 5(1):75–94
36. Crawford A (2015) Mining policy framework. International Institute for Sustainable Development.
37. Onditi F (2022) Mining policy frameworks. In: Gender inequalities in Africa's mining policies: a study of inequalities, resource conflict and sustainability . Singapore: Springer Singapore, pp 121–145
38. Website Information: https://www.responsibleminingfoundation.org/msat
39. Website Information: https://www.mining-technology.com/features/msat-responsible-mining
40. Bruckner KD (2023) Improving environmental and social practices in the mining sector is essential in the transition to renewable energy. J Energy Nat Resour Law 41(3):361–367
41. Fitzpatrick P, Fonseca A, McAllister ML (2011) From the whitehorse mining initiative towards sustainable mining: lessons learned. J Clean Prod 19(4):376–384
42. Franken G, Turley L, Kickler K (2020) Voluntary sustainability initiatives: An approach to make mining more responsible? In: The material basis of energy transitions. Academic Press. pp 169–186
43. Fraser J (2021) Mining companies and communities: Collaborative approaches to reduce social risk and advance sustainable development. Resour Policy 74:101144
44. Mayes R, McDonald P, Pini B (2014) 'Our'community: corporate social responsibility, neoliberalisation, and mining industry community engagement in rural Australia. Environ Plan A 46(2):398–413

## Publisher's Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.