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ENVIRONMENTAL DEGRADATION IN GOLD MINING SITES IN INDONESIA- A REFERENCE STUDY

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ABSTRACT: The gold mining sector in Indonesia is still facing challenges in achieving sustainable environmental management. The extraction and processing of essential minerals, such as gold, can have negative environmental consequences. For every tonne of gold produced, the following potential global warming effects are observed: 7.34.E+07 kg CO2 equivalent per tonne; freshwater aquatic ecotoxicity: 6.39.E+07 kg 1,4-DB equivalent per tonne. The foremost contributor to global warming impact is the consumption of electricity along with CO2 emissions. Key contributors to freshwater aquatic ecotoxicity include fuel oil, electricity, and Zn ion emissions. The combustion of coal in steam power plants results in the release of byproducts such as CO2, SOx, NOx, and PM2.5. Furthermore, the tailings from these mining operations often have elevated levels of heavy metals, which can greatly endanger the environment due to their contaminating nature. By employing advanced technology like cyclones, bag filters, and scrubbers, it is possible to reduce the emission of harmful gases from power plant emissions. Cyclones function by applying centrifugal force to separate solid particulates from exhaust gas. A bag filter operates as a filtration system designed to effectively capture tiny particles from exhaust gas through mechanical filtering techniques. Scrubbers work by introducing a cleaning solution into the exhaust gas stream, which initiates chemical reactions that transform hazardous gases into less harmful or more manageable molecules. Utilizing alternative liquid biofuels, such as biodiesel, in electrical systems is a vital approach for lessening the environmental footprint of the critical mineral industry. Biodiesel can lower emissions of SO2, particulate matter, and greenhouse gases during combustion compared to traditional fossil fuels like diesel. The use of microbial enhanced recovery methods in bioremediation can help diminish heavy metal concentrations in sediments. This is achieved through the use of microbial cells to concentrate metals using a biosorption approach. Future studies could involve evaluating the environmental performance of implementing cyclone, bag filter, and scrubber technologies in power plant emissions, alongside investigating the use of microbial improved recovery for metal bioremediation in tailings waste processing within Indonesia's critical mineral sector.

Key words: Ecotoxicity, Environment, Global warming, Gold mining, Indonesia, CO_2 emissions.

INTRODUCTION

Indonesia is among the top ten countries globally regarding significant amounts of nickel, gold, copper, tin, and bauxite reserves. As of 2022, Indonesia held the largest nickel reserves in the world, totaling approximately 21 million metric tons, which represents 20.57% of the global total. The country holds about 5.04% of the world's gold reserves, having extracted 70 metric tons of gold ore during that period. Indonesia has 2.71% of the global copper reserves and maintains a considerable level of copper ore production. With 17.31% of the world's tin deposits, Indonesia stands as the second-largest producer of tin ore globally. The

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bauxite reserves in Indonesia constitute approximately 3.19% of total global resources. Assuming a consistent production rate, it is projected that these mineral reserves will last between 10 to 47 years (**Geological Survey US, 2023**). Therefore, it is essential to conduct an environmental assessment of the crucial mineral mining and processing sector in Indonesia (**Sutikno *et al*., 2023**).

Open-pit mining and mineral extraction frequently result in deforestation and the obliteration of natural habitats. The removal of vegetation can lead to a reduction in biodiversity and negatively affect the local ecosystems (**Magidi and Hlungwani, 2023).** A substantial quantity of water is necessary for the extraction and processing of minerals. Excessive water use can deteriorate the quality and quantity of groundwater, jeopardizing the well-being of local communities and natural ecosystems (**Sengupta, 2021**). During the mining and processing of essential minerals, harmful gases such as carbon dioxide (CO2), nitrogen dioxide (NO2), and sulfur dioxide (SO2) are released into the atmosphere (**Bhat *et al*., 2022**). These gases are significant contributors to air pollution, which can result in respiratory issues and other health problems for humans while adversely impacting local ecosystems (**Singh and Ahirwar, 2022**). In the mineral refinement process, water is typically utilized to cleanse or separate minerals from the parent rock, which leads to the generation of liquid waste. This liquid byproduct may contain harmful elements, such as heavy metals, acids, or other hazardous substances. If this liquid waste is not properly processed or disposed of in the environment, it can lead to pollution of water sources, disruption of river ecosystems, and threaten aquatic life (**Meng *et al*., 2022**). The mineral refinement process also generates solid waste in the form of tailings or leftover rock. Poor management of these tailings can result in the presence of harmful substances, including heavy metals or radioactive materials, potentially contaminating soil and groundwater. Furthermore, the large-scale disposal of sediments can lead to landslides and other significant environmental catastrophes (**Sikdar *et al*., 2020**).

Prior studies have conducted evaluations of the environmental impacts linked to the extraction and processing of essential minerals (**Farjana *et al*., 2019**). Researchers have published assessments of environmental impacts concerning gold production **(Chen *et al*., 2018** in China**; Both Farjana *et al*., 2019; Strezov *et al*., 2021)** undertook an environmental impact analysis of the production of nickel, gold, copper, and bauxite in Australia. These earlier investigations have looked into a diverse array of effects within the critical minerals sector, including potential climate change impacts, terrestrial acidification potential, photochemical oxidant formation potential, particulate matter formation potential, freshwater eutrophication potential, terrestrial ecotoxicity potential, freshwater ecotoxicity potential, water depletion potential, fossil fuel depletion potential, and metal depletion potential. However, there has been a lack of earlier research offering a more thorough assessment of the impacts on human health, specifically regarding conditions such as asthma, cancer, severe Chronic Obstructive Pulmonary Disease (COPD), mild intellectual disability, osteoporosis, and renal dysfunction (**Farjana *et al*., 2019**).

This research seeks to evaluate the possible environmental and human health effects of Indonesia's critical mineral extraction and processing sector. The research examines potential environmental consequences, which include: (i) ecotoxicity on land, (ii) climate change, (iii) ecotoxicity in freshwater ecosystems, (iv) photochemical smog formation, (v) nutrient pollution, and (vi) acid rain. The study successfully met its aims by utilizing a Life Cycle Assessment (LCA) framework based on the ISO14040:2006 standard, which focuses on managing environmental impacts and evaluating life cycle concepts and frameworks. LCA is a comprehensive method employed to analyze the potential environmental impacts of a product throughout its entire life cycle (**ISO, 2006; Kheiralipour *et al*., 2021**).

Table 1 presents information from companies that remain operational, showcasing their production, exports, and domestic consumption. Fig. 1 illustrates Indonesian gold production sourced from Statistics Indonesia and the Ministry of Energy and Mineral Resources (Fig. 2), allowing the graphs to enhance one another; for instance, the data for the year 2016 is absent from Statistics Indonesia. Conversely, information from prior to 2015 is exclusively available through Statistics Indonesia.

Table 1. Top 15 Gold Companies

Company Name	Production [ton]	Export [ton]	Domestic [ton]
Antam Co. (UBPP Logam Mulia)	44.13	17.60	13.70
Freeport Indonesia	28.01	11.63	19.51
Agincourt Resources	12.17	11.93	0.00
Tambang Tondano Nusajaya	6.8	7.03	0.00
Nusa Halmahera Minerals	5.1	5.55	0.00
J Resources Bolaang Mongondow	2.6	2.78	0.00
Indo Muro Kencana	1.92	1.87	0.00
Amman Mineral Nusa Tenggara	1.73	0.83	1.17
Bumi Suksesindo	1.56	1.56	0.00
Antam Co. (UBPE Pongkor)	1.42	1.05	0.00
Meares Soputan Mining	1.33	1.34	0.00
Natarang Mining	0.9	0.74	0.00
Kasongan Bumi Kencana	0.86	0.86	0.00
Sago Prima Pratama	0.49	0.49	0.00
Sultan Rafli Mandiri	0.01	0.00	0.00

Source: Meutia *et al*. (2022).

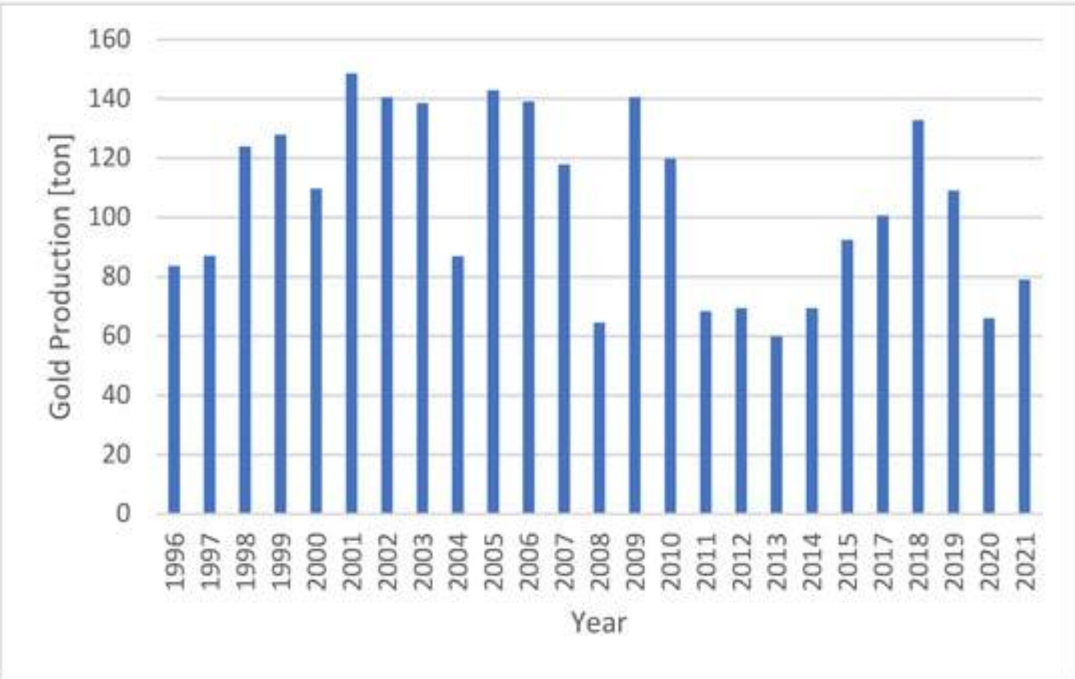

Fig. 1. Indonesian Gold Production

Source: Meutia *et al*. (2022)

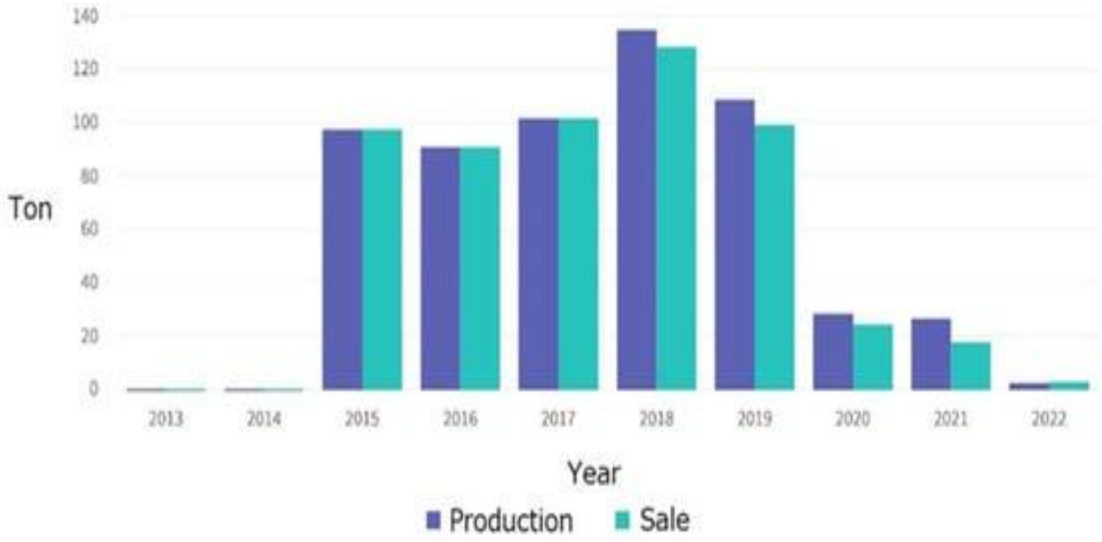

Fig. 2. Gold production in Indonesia

Source: Meutia *et al*. (2022).

The oldest producer in Java, ANTAM Co., was founded as a state-owned enterprise in 1968 following the amalgamation of various national projects and mining firms. Recently, some local governments have partnered with private companies to engage in gold mining through shared ownership, such as the collaboration between the South Tapanuli Regency Government and the North Sumatra Provincial Government in the gold mining regions

Methodology

Goal and scope

The aim of this research is to evaluate the potential environmental impacts associated with gold mining operations in Indonesia. The environmental effects of gold production were determined using a mid-point approach. This evaluation employed the Life Cycle Assessment (LCA) methodology, specifically adhering to the ISO 14040 standard established in 2006 (**ISO, 2006**) titled "Management of Environmental – Assessment of Life Cycle – Principles and Framework." The Attributional Life Cycle Assessment (ALCA) method was chosen over the Consequential Life Cycle Assessment (CLCA) approach because it applies normative allocation rules and initial inventory data that typically reflect national or global averages. The ALCA was adjusted proportionally to align with the functional unit in a linear fashion. The intended audience includes the Indonesian government and key stakeholders within Indonesia's critical mineral sector.

An evaluation is performed regarding the possible environmental and human health impacts associated with the mining and processing of nickel, gold, copper, tin, and bauxite. This assessment considers the discharge of pollutants into air, water, and soil, along with the resources consumed in the process. The scope of this Life Cycle Assessment (LCA) analysis is determined as gate-to-gate. Emissions produced during essential mineral mining, processing, and waste management operations are utilized as inventory data to evaluate the environmental and human health impacts. This analysis includes both material and energy resources. The functional unit for this study is defined as the production of one tonne of critical minerals. This research compares the environmental repercussions of producing one tonne of gold. Figure 3 illustrates the system boundary of the gold mining and processing sectors in Indonesia.

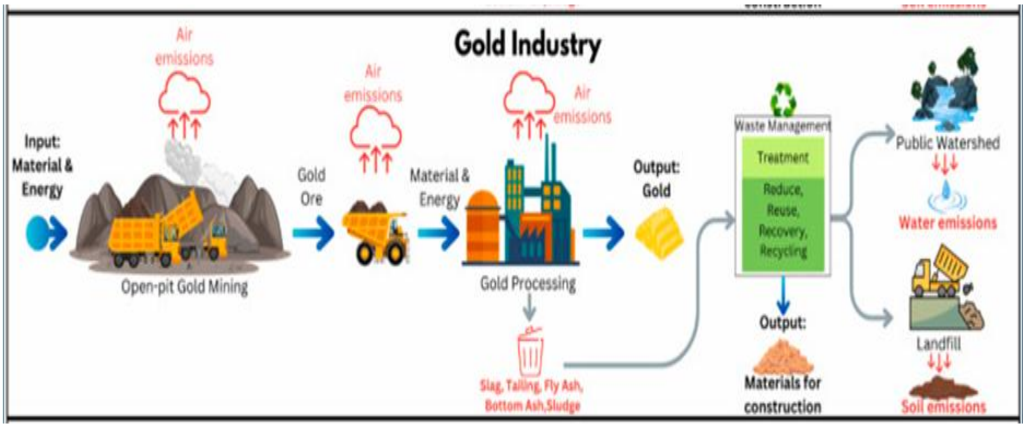

Fig. 3. The system boundaries of the gold mining and processing industries in Indonesia

Source: Wahyono *et al*. (2024).

Open-pit mining, the processing of critical minerals, and the management of waste are the three primary activities involved in gold production. The mining and processing units require resources in the form of materials and energy. The result from the mining unit is gold. The processing machinery requires both raw materials and energy. The end product of the processing unit is also gold. This research is grounded in the following assumptions.

The fuel oil referred to in this context is Marine Fuel Oil (MFO). 2) The particular type of diesel utilized is Industrial Diesel Oil (IDO). 3) Steam power plants employ bituminous coal. 4) The main source of biodiesel is palm oil biodiesel. 5) The water used for input is obtained from a river. 6) After extensive monitoring, emissions from the air, water, and soil are released into the surrounding environment.

The waste generated from operational activities includes Hazardous and Toxic Materials (HTM) as well as non-HTM waste. The disposal of this waste follows all relevant regulations. Efforts are made to minimize the negative impacts of waste in order to prevent disruption to community activities in areas close to operations. Both HTM and non-HTM waste is managed through the Reduce-Reuse-Recover-Recycle (4R) framework. It is essential to have a complaint system, established protocols, and suitable infrastructure in place to manage any incidents involving HTM spills. This approach is vital for reducing incidents and preventing pollution that could arise from accidents with potentially harmful effects. There were no major violations in operational areas that caused harm to the surrounding ecosystems or communities.

In contrast, non-HTM waste can be efficiently managed through the 4R strategy for non-biodegradable inorganic materials. Meanwhile, organic waste is subjected to separation, decomposition, recycling, and utilization processes. Various innovative methods are employed to minimize the environmental effects of HTM waste by finding ways to reuse it. Conversely, HTM waste that cannot be recycled will be directed to a certified third-party service. The organization's waste is being handled by authorized partners, as verified. These partners have implemented waste management practices that adhere to relevant standards, including stabilization and solidification, fuel substitution, and disposal in eco-friendly landfills. Similarly, non-HTM waste that cannot be repurposed will be directed to a final disposal site. Waste management practices for both HTM and non-HTM waste is established in accordance with applicable regulatory frameworks and is subjected to ongoing monitoring and evaluation.

Slag is the byproduct generated at a mineral processing facility when metals are extracted from their ores through high-temperature techniques. Recycled slag is used in concrete production. Presently, companies utilize slag for internal uses such as road foundations, yard surfaces, and concrete-related construction materials. Since the classification of slag has shifted from hazardous waste to non-hazardous waste, it can now be used for commercial purposes. Tailings are the leftover materials resulting from the hydrometallurgical processes used to refine gold ore. Green Fine Aggregate (GFA) is an eco-friendly building material derived from recycled tailings. Fly Ash and Bottom Ash, collectively referred to as FABA, are byproducts created during the combustion of coal in steam power plants and electric precipitator facilities. FABA is employed as a construction material for internal purposes. Although FABA was not previously classified as HTM waste, it holds the potential to be converted into a product of considerable external value.

Inventory data

Previous studies were conducted to gather information on air, water, and soil emissions, along with material and energy inputs within Indonesia's gold sector (**Milovanoff *et al*., 2020 and Virginia *et al*., 2020**). The inventory data for the gold industry mainly emphasizes emissions as well as material and energy inputs. The emissions inventory data is essential for pinpointing the key chemical characteristics and gas emissions that contribute to detrimental environmental impacts in Indonesia's vital minerals sector. Table 2 provides details about the gold mining and processing industries in Indonesia.

Impact assessment

This research examines the potential environmental impacts of emissions into air, water, and soil, as well as the inputs of materials and energy, related to critical mineral companies in Indonesia. The CML-IA Baseline approach is employed to evaluate the possible environmental repercussions. The environmental impacts considered include terrestrial ecotoxicity, global warming potential (GWP100a), aquatic ecotoxicity in freshwater, photochemical oxidation, eutrophication, and acidification (**Kheiralipour *et al*., 2021**). Evaluating sustainability is mainly an ethical consideration, as there is no single value but rather a spectrum of values that differ in importance. For product developers or decision-makers, grasping the monetary value that individuals are willing to pay is essential. This understanding aids them in avoiding decisions that may result in environmental damage, especially if they would personally experience the repercussions of such harm. Product developers and stakeholders should also refrain from spending more than necessary, thus market values or estimated market values are considered relevant indicators for the cost of damage (**Steen, 2016**).

Potential Environmental Impacts of Critical Mineral Industry in Indonesia

Indonesia's gold mining and processing sectors continue to face issues concerning emissions management and possible environmental repercussions. Table 3 outlines the potential environmental impacts associated with Indonesia's critical mineral sector. Figure 4 illustrates the primary factors that lead to environmental impacts resulting from emissions affecting the air, water, and soil, along with the inputs of materials and energy.

Acidification

The possible ramifications of acidification caused by SOx, NOx, ammonium, hydrochloric acid, and hydrofluoric acid emissions through air, water, and soil are measured in units of SO2 equivalent (**Bordbar *et al*., 2023**). Gold extraction in Indonesia has a potential acidification effect of 2.88.E+05 kg SO2 eq/t (Table 3). The primary contributors to acidification impacts on the gold sector are the use of fuel oil, electricity, diesel, and biodiesel, accounting for 98.53% of the total effect (electricity). The combustion of coal produces NOx. The critical mineral sector in Indonesia relies on coal as a fuel source for steam power plants (**Paraschiv and Paraschiv, 2020**). NOx in the atmosphere can interact with precipitation to form acidic compounds. These acidic substances will seep into the water and soil, resulting in the acidification of the surrounding environment (**Wahyono *et al*., 2022**).

The emission of SOx from the critical mineral sector significantly contributes to environmental acidification. When SOx reacts with water vapor in the atmosphere, it can create sulfuric acid. This acid can inflict significant damage on the environment. The effects are felt both locally and far away, disrupting the ecological balance (**Bhat *et al*., 2022**). In the gold mining company, NOx emissions amounting to 3.91 kg can influence acidification by 0.00067 %.

Table 2. Inventory data of the gold mining and processing industries in Indonesia

Categories	Parameter	Unit	Gold mining and processing
Input Material and Energy	Marine Fuel Oil	L	–
	Industrial Diesel Oil	L	873,210
	Coal	Kg	–
	Petrol	L	–
	Electricity	KWh	59,883,792
	Water	KL	9696.35
	Biodiesel B30	L	–
	Gold ore	T	3
	Gold	T	1
Missions			
	CO2	T	5910
	SOx	Kg	0.04
	NOx	Kg	3.91
	PM	Kg	0.02
	TDS	Mg	–
	TSS	Mg	–
	Ni	Mg	–
	Zn	Mg	–
	Cd	Mg	–
	Cu	Mg	–
	Pb	Mg	0.098
	Hg	Mg	0.0075
	As	Mg	0.001
	Cr	Mg	–
	Cu	Mg	4.43
	Pb	Mg	2660
	Ni	Mg	–
	As	Mg	62,100
	Hg	Mg	790
	Cr	Mg	–
	Cd	Mg	–
	Zn	Mg	–
	As	Mg	–
	V	Mg	–

Source: Wahyono *et al*. (2024)

Table 3. The environmental impact of gold production in Indonesia

Impact category	Reference unit	Gold production
Acidification	kg SO2 eq/t	2.88.E+05
Eutrophication	kg PO4--- eq/t	4.00.E+05
Fresh water aquatic ecotox.	kg 1,4-DB eq/t	6.39.E+07
Global warming (GWP100a)	kg CO2 eq/t	7.34.E+07
Photochemical oxidation	kg C2H4 eq/t	9.24.E+03
Terrestrial ecotoxicity	kg 1,4-DB eq/t	1.09.E+05

Eutrophication

The potential effects of eutrophication or nutrification are assessed by quantifying the amount of phosphate equivalent, measured in kilograms, that flows into the water source (**Bordbar *et al*., 2023**). The extraction and processing of one tonne of gold in Indonesia can lead to potential acidification impacts of 4.00.E + 05 kg PO4--- eq/t (Table 3). The primary factor contributing to the detrimental effects of eutrophication in gold mining and refining is electricity consumption, which constitutes 99.86%. The presence of NOx in the water enhances the nutrient levels in the aquatic environment (**Wahyono *et al*., 2022).** Eutrophication refers to the slow accumulation of minerals and nutrients, particularly nitrogen and phosphorus, within a water body or a significant portion of it (**Kowalczewska-Madura *et al*., 2022**).

Global warming potential

The influence of greenhouse gas emissions is evaluated by comparing it to the global warming potential (GWP) of carbon dioxide over a 100-year timeframe. This evaluation is represented in carbon dioxide equivalent units. Table 3 illustrates the potential global warming effect associated with the production of one tonne of gold in Indonesia: 7.34.E+07 kg CO2 eq/t. The primary contributor to the global warming impact on the gold industry is electricity consumption, which accounts for 91.41% of the total (Fig. 4). The burning of coal in steam-powered generators and diesel-powered mining vehicles contributes to the emission of carbon dioxide (**Paraschiv and Paraschiv, 2020).** The presence of CO2 and other greenhouse gases (GHGs) in the Earth's atmosphere causes infrared energy from the sun to be reflected back to the Earth's surface, leading to global warming (**Wahyono *et al*., 2020**). Additionally, the effects include the gradual melting of polar ice caps, leading to rising sea levels, as well as changes in the global climate (**Bordbar *et al*., 2023**).

Ecotoxicity

Environmental toxicity can be assessed through two primary impact categories: terrestrial and freshwater. The established unit for measuring the toxicity potential of pollutants in aquatic and terrestrial ecosystems is the kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DB eq). The extraction and processing of one tonne of gold in Indonesia results in a potential freshwater aquatic ecotoxicity impact of 6.39.E+07 kg 1,4-DB eq/t. Furthermore, producing one tonne of gold in Indonesia leads to potential terrestrial ecotoxicological effects of 1.09.E+05 kg 1,4-DB eq/t (Table 3). Electricity consumption (Fig. 4) is the leading contributor to terrestrial ecotoxicity, making up 99.09%, and freshwater aquatic ecotoxicity, accounting for 99.88%, within the gold sector (**Murdifin *et al*., 2019**).

Photochemical oxidation

The Photochemical Ozone Production Potential (POCP) is quantified in kilograms of ethylene equivalent (kg C2H4 eq). Photochemical oxidation, often referred to as summer haze, takes place when Volatile Organic Compounds (VOCs) and NOx react under the influence of ultraviolet radiation. Table 3 illustrates the impact of photochemical oxidation resulting from the production of one tonne of gold in Indonesia: 9.24.E + 03 kg C2H4 eq/t. The use of electricity is the main contributor to the global warming effects associated with the gold and bauxite sectors, representing approximately 98.15 % and 68.63 % of their respective impacts. Common solvents used in mineral extraction processes include methanol, toluene, and xylene. Lubricants like diesel oil and oil-based products may contain VOCs. VOCs can be produced during the combustion of mining machinery and equipment, particularly when utilizing diesel and petroleum as fuels. Chemicals involved in the mineral processing operation, including surfactants, thickening agents, and solvents, typically contain VOCs (**Liang *et al*., 20**22).

Limitations and recommendations

The limitations of this study stem from the use of secondary data sources, which were obtained from sustainability reports of companies operating in Indonesia's gold sector. Additionally, reference materials from scholarly journals are incorporated. When it comes to data representation, it is important to recognize that the data sources possess varying publication years. Variations in publication dates may influence the reliability and relevance of

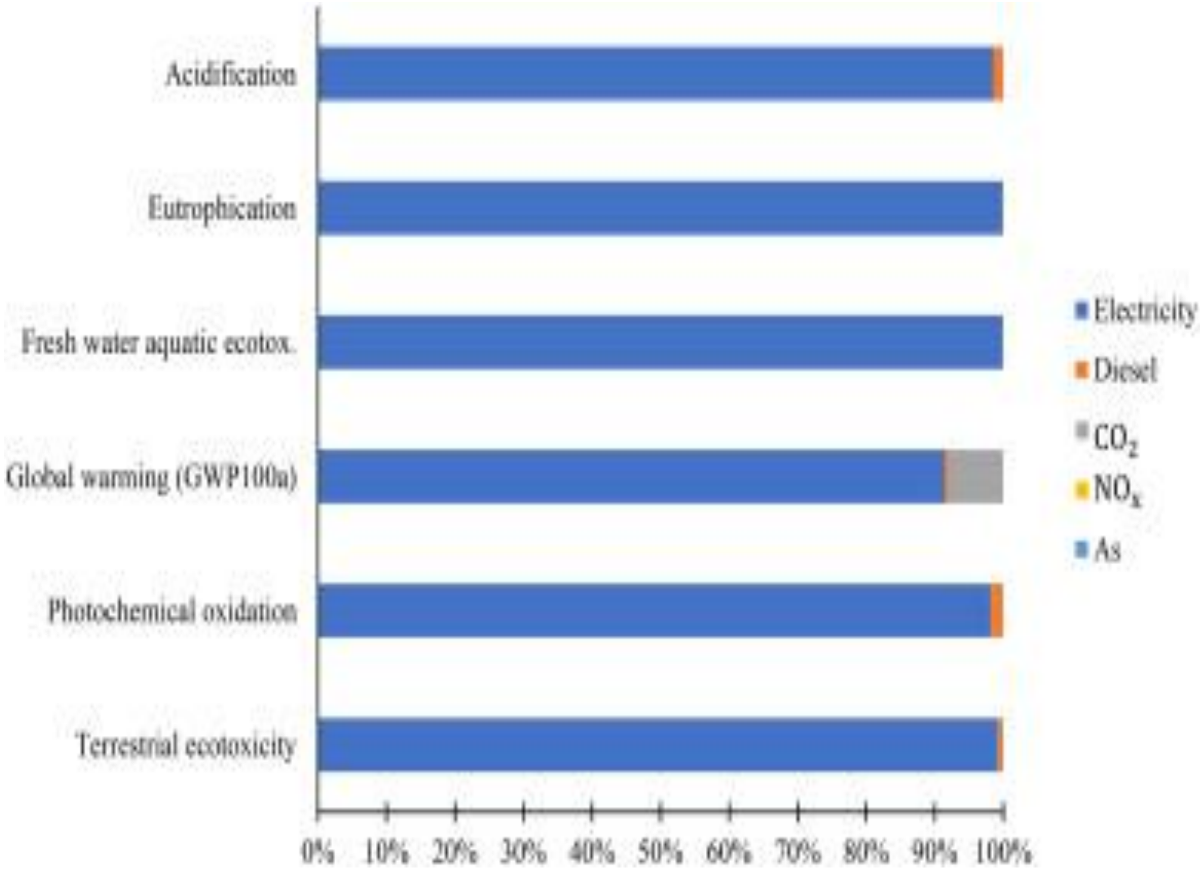

Fig. 4. The environmental impacts contributors of the gold

Source: Wahyono *et al*. (2024).

the research findings. Therefore, to enhance the accuracy and consistency of the data, it is suggested that future research utilize primary data sources collected within the same timeframe. Primary data is not only more relevant but also allows researchers to gain deeper and more accurate insights. This approach aims to minimize bias that could arise from discrepancies in the publication years of secondary data sources. Moreover, future research can expand its focus to include assessments of the environmental performance of technologies such as cyclones, bag filters, and scrubbers used in power plant exhaust systems. These technologies have considerable potential to reduce emissions and improve air quality around industrial sites. It is essential to emphasize the investigation of microbial enhanced recovery methods for metal bioremediation in tailings management within Indonesia's vital mineral mining sector.

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التــدهـــور البيئـــي فـــي مواقع تعـدين الـذهــب في إنــدونيسـيا – دراســـة مرجعية

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لا يزال قطاع تعدين الذهب في إندونيسيا يواجه تحديات في تحقيق الإدارة البيئية المستدامة. يمكن أن يكون لاستخراج ومعالجة المعادن الأساسية، مثل الذهب، عواقب بيئية سلبية. لكل طن من الذهب المنتج، يتم ملاحظة التأثيرات المحتملة التالية للاحتباس الحراري العالمي: 07.7.34 + E كجم مكافئ ثاني أكسيد الكربون لكل طن؛ السمية البيئية للمياه العذبة: 07.6.39 + E كجم مكافئ DB-1,4 لكل طن. المساهم الأول في تأثير الاحتباس الحراري العالمي هو استهلاك الكهرباء إلى جانب انبعاثات ثاني أكسيد الكربون. تشمل العوامل الرئيسية المساهمة في السمية البيئية للمياه العذبة انبعاثات زيت الوقود والكهرباء وأيونات الزنك. يؤدي احتراق الفحم في محطات الطاقة البخارية إلى إطلاق منتجات ثانوية مثل ثاني أكسيد الكربون وأكاسيد الكبريت وأكاسيد النيتروجين والجسيمات الدقيقة 2.5. وعلاوة على ذلك، غالبًا ما تحتوي مخلفات عمليات التعدين هذه على مستويات مرتفعة من المعادن الثقيلة، والتي يمكن أن تعرض البيئة للخطر بشكل كبير بسبب طبيعتها الملوثة. من خلال استخدام التكنولوجيا المتقدمة مثل الأعاصير ومرشحات الأكياس وأجهزة التنظيف، من الممكن تقليل انبعاث الغازات الضارة من انبعاثات محطات الطاقة. تعمل الأعاصير بتطبيق قوة الطرد المركزي لفصل الجسيمات الصلبة عن غاز العادم. يعمل مرشح الأكياس كنظام ترشيح مصمم لالتقاط الجسيمات الدقيقة من غاز العادم بفعالية من خلال تقنيات الترشيح الميكانيكية. تعمل أجهزة التنظيف عن طريق إدخال محلول تنظيف في تيار غاز العادم، مما يبدأ تفاعلات كيميائية تحول الغازات الخطرة إلى جزيئات أقل ضررًا أو أكثر قابلية للإدارة. يعد استخدام الوقود الحيوي السائل البديل، مثل الديزل الحيوي، في الأنظمة الكهربائية نهجًا حيويًا لتقليل البصمة البيئية لصناعة المعادن الحيوية. يمكن للديزل الحيوي خفض انبعاثات ثاني أكسيد الكبريت والجسيمات والغازات المسببة للانحباس الحراري أثناء الاحتراق مقارنة بالوقود الأحفوري التقليدي مثل الديزل. يمكن أن يساعد استخدام طرق الاسترداد المعززة بالميكروبات في المعالجة البيولوجية في تقليل تركيزات المعادن الثقيلة في الرواسب. يتم تحقيق ذلك من خلال استخدام الخلايا الميكروبية لتركيز المعادن باستخدام نهج الامتصاص البيولوجي. يمكن أن تشمل الدراسات المستقبلية تقييم الأداء البيئي لتطبيق تقنيات الأعاصير ومرشحات الأكياس والمنظفات في انبعاثات محطات الطاقة، إلى جانب التحقيق في استخدام الاسترداد الميكروبي المحسن للتطهير البيولوجي للمعادن في معالجة نفايات المخلفات داخل قطاع المعادن الحيوي في إندونيسيا.

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