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RISK ANALYSIS OF EXPOSURE TO WORKER HEALTH AND ECOSYSTEMS AT TIN SMELTERS

Ferly Oktriyedi[1]*, Lela Handayani[2], Dedek Sutinbuk[1]
[1]Master of Public Health Science, Universitas Anak Bangsa, Jl. Pinus I No. 693, Kacang Pedang, Pangkal Pinang, Bangka Belitung 33684, Indonesia
[2]Diploma III Midwifery Study Program, Akademi Kebidanan Pretasi Agung, Jl. Rangga Lawe, Campus Complex Tulang Bawang, Lampung 34682, Indonesia
*ferlyoktriyedi7@gmail.com

ABSTRACT
Indonesia, particularly Bangka Belitung Province, is one of the world's largest tin producers, supporting exports and state revenue. Tin smelting activities (smelters) are a vital part of this metal's production chain. The focus of this research is on production activities, tailings disposal, and chemical refining, which have the potential to cause environmental pollution and health risksThis research is important to provide evidence-based insights into environmental and occupational hazards of tin smelting, enabling targeted mitigation strategies and promoting sustainable industrial practices without compromising public health or environmental integrity. This study used descriptive field observation methods at the tin smelter in June 2025, focusing on the production process, waste management, and occupational safety practices. Data were collected through direct observation and semi-structured interviews with workers, OHS officers, and operational managers. The data were then analyzed qualitatively to identify and describe potential environmental pollution and occupational health risks. This study confirms that tin mining activities, from land clearing to refining, have significant impacts on the environment, public health, and occupational safety. Soil, water, and air pollution from solid and liquid waste and exposure to heavy metals have been proven to threaten the sustainability of the ecosystem and the socio-economic well-being of surrounding communities. Furthermore, mine workers face a high risk of occupational diseases and physical and mental stress. Therefore, a comprehensive mitigation strategy is needed through the implementation of waste management technology, strict OHS standards, environmental quality monitoring, and public health education. These efforts are key to balancing tin industry productivity with sustainable development principles.

Keywords: environmental health; environmental pollution; occupational deasis; occupational health; tin mining

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INTRODUCTION

Indonesia, particularly Bangka Belitung Province, is known as one of the world's largest tin producers, contributing significantly to exports and state revenue (Sulista & Rosyid, 2022). Tin smelting is a crucial stage in the metal production chain as it determines the quality of the final product, which is ready for global marketing (Prihatin & Satriando, 2024). However, this process produces residues and waste containing heavy metals, which, if not managed properly, can cause environmental pollution and health risks to surrounding communities (Haghighizadeh et al., 2024; Oladimeji et al., 2024). Solid waste from the smelting process has been found to contain heavy metals such as lead (Pb), cadmium (Cd), and copper (Cu). The presence of these heavy metals is dangerous due to their toxicity, persistence, and ability to accumulate in the food chain (Adnan et al., 2024). management conditions involving open dumping without protective systems increase the risk of soil and groundwater contamination around industrial sites (Fayomi et al., 2025).

If this contamination continues, heavy metal bioaccumulation will occur in aquatic and terrestrial organisms, which can trigger long-term toxic effects such as impaired kidney function, nervous system damage, and even carcinogenic effects in humans (Ajala et al., 2025; Laoye et al., 2025). This demonstrates that smelters without waste management systems that meet international standards have the potential to cause environmental and public health crises. Furthermore, workers in the smelter industry face direct exposure to metal dust and chemical vapors during the production process. Chronic exposure to heavy metals has been shown to increase the risk of respiratory disorders, neurotoxicity, cardiovascular disease, and cancer (Martin & Larivière, 2014; Rai et al., 2019; Sullivan, 2014). A study in China showed that blood levels of lead and cadmium (Pb) and lead (Cd) in smelter workers significantly exceeded the WHO health threshold, confirming the presence of serious hazards in the workplace (Zhang et al., 2024).

Observations at the smelter industry in Bangka Belitung in June 2025 revealed intensive combustion, tailings disposal, and chemical refining activities. These processes have the potential to produce metal particulates, hazardous gas emissions, and liquid waste that can degrade the surrounding environment (Dehkordi et al., 2024). Therefore, systematic identification of pollution sources and evaluation of workplace conditions in the smelter industry are crucial. Field observations and interviews provide a clear picture of the relationship between tin industry activities and health risks from heavy metal exposure. The objectives of this study are to identify and describe the potential sources of environmental pollution and occupational health hazards in tin smelting activities, to assess the level of exposure to heavy metals among workers, and to provide recommendations for improving waste management, occupational safety, and environmental protection in the tin smelter industry.

METHOD

Research Design

This study used a descriptive field observation method to identify potential health impacts and environmental pollution caused by the operational activities of the tin smelter industry. The focus was on understanding the phenomenon in depth, particularly regarding exposure risks to worker health, the environment, and OHS aspects in the tin smelting industry. The descriptive approach was chosen because it can provide a factual picture of real-world conditions, particularly in the context of occupational health risks and environmental pollution in the extractive industry (Creswell & Poth, 2018).

Location and Key Informants

This research was conducted directly at one of the smelter sites in June 2025, focusing on three main aspects: the production process, waste management, and occupational safety implementation. Key informants in this study consisted of workers: P1 (excavator operator), P2 (pump & jetting operator), P3 (washing/jig operator); OHS Officer: HSE (certified), and operational manager: MO (mining & smelting management).

Sampling Techniques

Data collection was conducted using two main techniques. First, direct observation of smelting, crystallization, and waste management activities was carried out to identify potential sources of pollution and occupational health risks, given that these processes often generate hazardous dust and gas emissions (Adnan et al., 2024). Observations were performed on-site at different stages of production, including raw material handling, smelting, chemical refining, and tailings disposal. During these observations, the researcher systematically recorded the types of activities, the presence of dust and gas emissions, worker behavior, and use of personal protective equipment (PPE).

Second, semi-structured interviews with workers, OHS officers, and operational managers were conducted to obtain information regarding chemical exposure, PPE use, health complaints, and management practices (Kappel et al., 2026). Participants were selected purposively to include those directly involved in smelting and waste handling, ensuring that a representative range of experiences and observations was captured. Each interview lasted 30–60 minutes and was audiorecorded with consent, then transcribed for analysis.

Data Analysis

Data collected from observations, interviews, and documentation studies were then analyzed qualitatively. This analysis involved systematically identifying, categorizing, and describing various potential hazards and risks arising in smelting and waste management activities. Observational notes and interview transcripts were coded according to hazard type (chemical, physical, ergonomic) and exposure pathway, allowing for a comprehensive understanding of occupational and environmental risks associated with tin smelting.

RESULT

The following section presents findings from field observations and interviews conducted in the mining and smelting environment. Data were collected to identify key issues related to occupational health and safety (OHS), environmental management, and operational practices. Observations focused on visible conditions, equipment, and processes, while interviews provided insights from workers, supervisors, and safety officers regarding current practices and challenges. These combined findings are summarized in Table 1, which highlights key areas such as dust control, slope stability, water management, smelting operations, and safety system compliance.

Table 1.
Observation and Interview Results in the Mining and Smelting Environment

Key Issue	Field Observation	Interview
Dust & TSS during land clearing	Dust levels increase during land clearing; water trucks operate periodically; topsoil and overburden piles are separated; rapid drainage needed during rainfall.	P1: dust and slope stability; topsoil separated; quick drainage. P3: water trucks circulate; signs and safe routes available.
Slope and haul road stability	Work slopes and haul roads are key safety control points.	P1: daily checklist for slopes and haul roads.
Gravity washing & particle size control	Materials are directly sent to the gravity-based washing unit.	P3: monitors particle size to maintain recovery. MO: particle size control is key to quality.
Wet mining: high-pressure jetting	Pump and slurry pipe operations; slippery areas present potential hazards; technical access around pipes is supervised.	P2: jetting hazards; mandatory use of face shield, goggles, gloves, and boots. HSE: jetting SOP and permit-to-work system in place.
Water management: settling pond & recirculation	Flow directed to settling ponds; clear water is reused.	P3: uses coagulant when water becomes turbid; recycles water to the mining front. MO: multi-chamber ponds; bypass to retention pond during heavy rain.
Rotary dryer: heat, noise, dust	Area is hot and noisy, with dust risk; operation panel interlocks observed.	P3: uses earplugs and particulate masks; interlocks prevent panel opening during operation. HSE: annual audiometry program.
High-temperature smelting (≈1200–1400°C)	Smelting process at high temperature; potential for fume/heat exposure.	P3: furnace operates at 1200–1400°C; bag filters and chimney in use; ΔP alarm alerts maintenance. HSE: attention to vapor/particle exposure of As, Pb, Bi, Ni, Cu.
Purification, crystallization & hazardous waste (dross/slag)	Separation based on melting point; labeled hazardous waste containers.	P1: Pb/Bi remain molten; dross placed in hazardous waste containers. MO: dross/slag managed by licensed waste handler. HSE: applies hierarchy of control + bundwall for storage.
Transition points between process stages as risk hotspots	Material transfer areas (washing → dryer; smelting → storage) show high activity density.	HSE: dust/fume exposure and heat contact most frequent at transition points.
PPE compliance & behavior	PPE observed in critical areas; compliance looser in transition zones.	HSE: good compliance in wet fronts, sometimes lax in transit areas; promotes behavior-based safety.
OHS & Environmental Systems (ISO 45001/14001)	Occupational health, safety, and environmental management practices implemented; documentation visible on logs/labels.	MO: gradual implementation of ISO 14001 & 45001. HSE: active HIRADC, toolbox meetings, and LOTO procedures.

Observations and interviews in the mining and smelting environment identified several key operational and safety issues. During land clearing, dust levels increase and are managed through water truck operations, topsoil separation, and rapid drainage. Slope and haul road stability are closely monitored using daily checklists to prevent accidents. In the gravity washing process, particle size control is emphasized to maintain product recovery and quality. Wet mining presents hazards due to high-pressure spray and slippery surfaces, necessitating strict PPE use and adherence to SOPs and a permit-to-work system. Water management relies on multi-chamber settling ponds, which recycle clean water back into the operation, with the addition of coagulants when necessary. Rotary dryers pose heat, noise, and dust risks, which are mitigated through the use of PPE and regular health monitoring, including annual audiometry. The smelting process, operating at 1200–1400°C, poses significant risks from heat and toxic fumes (As, Pb, Bi, Ni, Cu), which are controlled through bag filters, flues, and an alarm system. Refining produces hazardous waste (dross/slag), which is stored in labeled containers and shipped to licensed handlers. Transition points between stages, such as washing to drying and smelting to storage, are identified as high-risk areas due to exposure to dust, fumes, and heat.

PPE compliance is generally good in critical areas but less consistent in transit zones, highlighting the need for a behavior-based safety program. Overall, the phased implementation of ISO 45001 and ISO 14001 supports systematic safety and environmental management through practices such as HIRADC, toolbox meetings, and LOTO procedures.

DISCUSSION

Land Clearing and Overburden Removal

The tin mining process at the observation site uses a relatively simple open-pit mining method, beginning with the removal of overburden to access economically viable ore. This initial stage generates large amounts of solid waste in the form of soil, waste rock, and mud. If waste is not managed properly, it can become a major source of pollution, increasing water turbidity, erosion, and the transport of heavy metals to water bodies (Abubakar et al., 2022; Akhtar et al., 2021; Njewa et al., 2025). In addition to solid waste, mining activities also generate water and air pollution. Increased water turbidity due to fine sediment disrupts photosynthesis in aquatic plants and aquatic ecosystems (Bănăduc et al., 2024; Damseth et al., 2024; Tonelli & Tonelli, 2020). Meanwhile, the use of heavy equipment and the smelting process produce particulate emissions and exhaust gases that worsen air quality and increase the risk of respiratory diseases (Behinaein et al., 2023; Matei et al., 2025).

The accumulation of these physical and chemical impacts directly reduces community access to clean water and productive land, thereby undermining local food security and socio-economic well-being (Ejiohuo et al., 2025). Furthermore, the destruction of fish and wild plant habitats reduces biodiversity and reduces the ecosystem's capacity to provide essential ecological services (Kumar et al., 2023; Nimma et al., 2025). This condition increases the risk of ecological disasters such as floods and landslides, especially in areas with poor drainage or fragile geology (Shu et al., 2024; Q. Wang et al., 2025). Chronic exposure to heavy metals such as Pb, As, and Hg bioaccumulates in the food chain and can enter the human body through food, water, and dust inhalation (Angon et al., 2024; Shetty et al., 2025). Impacts include central nervous system disorders, kidney damage, developmental abnormalities in children, and even skin, lung, and bladder cancers (Silva et al., 2025). Limited access to health services in mining areas exacerbates community vulnerability, as health impacts are often only detected at a chronic stage (Lo et al., 2024).

Mining Process (Dry and Wet Methods)

In the tin mining industry, there are two main methods used: dry mining and wet mining. In the dry method, tin ore obtained from land is extracted using heavy equipment and then transported directly by truck to the processing site. Although this method is considered simple, its environmental impacts are significant, as it can cause damage to soil structure, vegetation degradation, and increased erosion, which can worsen land stability (Irawan et al., 2014; Z. Wang et al., 2025). The use of heavy equipment also generates vibrations that can potentially alter soil morphology and increase the risk of landslides in open-pit mines (Lu et al., 2024).

In contrast, in the wet mining method, tin ore mixed with mud is transported to a washing area using a system of pumps and pipes. This washing process utilizes high-pressure water to separate the tin ore from impurities such as sand and clay using the principle of gravity, based on differences in density (Nzeh & Popoola, 2024). The advantage of this method is its efficiency in ore separation, but its use requires significant amounts of water, increasing the risk of exploiting water resources. The liquid waste (tailings) produced from this process can pollute water bodies if not properly managed, as it contains heavy metals that are harmful to aquatic ecosystems (Abbadi & Mucsi, 2024; Araujo et al., 2022). From an occupational health perspective, tin mining activities, both dry and wet methods, and the smelting process, can pose serious health risks to workers. Exposure to dust particles from soil and rock during dry mining can trigger lung diseases such as pneumoconiosis and chronic bronchitis (Rumchev et al., 2023).

Smelting Process

After the washing stage, tin ore is typically dried using a rotary dryer to reduce the moisture content before being mixed with anthracite coal and additional materials (flux). The flux helps bind impurities during the smelting process and accelerates chemical reactions in the electric furnace (Maldybayev et al., 2024). The smelting process is carried out at high temperatures, between 1200–1400°C, with the goal of producing crude tin metal ready for further processing (Chen et al., 2019). This stage requires significant electrical energy and produces exhaust gases that have the potential to pollute the air if not equipped with modern emission control or filtration systems (Elehinafe et al., 2024; Yao et al., 2018).

In practice, the smelting process faces several technical challenges. One is the melting temperature exceeding the standard due to variability in ore composition, which leads to longer smelting times and reduced energy efficiency. Furthermore, some tin can be lost through evaporation when operating temperatures exceed the optimum limit, reducing production yields and increasing the potential for the formation of slag containing heavy metals. Improperly managed slag can contaminate soil and groundwater, posing long-term risks to the surrounding ecosystem (Marzoughi & Pickles, 2024).

During the leaching and smelting processes, workers are also potentially exposed to hazardous heavy metals such as lead (Pb), arsenic (As), and cadmium (Cd), which can cause neurological disorders, kidney damage, and cancer if accumulated over the long term (Marzoughi & Pickles, 2024). Furthermore, exposure to extreme heat during smelting increases the risk of heat stress and dehydration, especially in facilities with inadequate ventilation. Therefore, implementing occupational safety standards and providing personal protective equipment (PPE) are crucial steps to minimize health risks for mine workers (Chetty et al., 2024).

Crude Tin Storage

The post-smelting stage of crude tin storage requires proper infrastructure and waste management systems because the product still contains toxic metals such as arsenic, nickel, and copper. If not managed to adequate standards, storage can contaminate soil and groundwater (Ankit et al., 2021; Haes & Lucas, 2024). To reduce impurities, additional purification with aluminum and sulfur is carried out, but this process also produces heavy metal-rich waste that has the potential to pollute water bodies and pose a risk of chronic exposure (Aziz, 2024). Beyond environmental impacts, smelting activities pose serious risks to workers. Mineral dust containing Pb, As, and Mn can be inhaled, triggering lung diseases such as pneumoconiosis and chronic bronchitis (Cohen et al., 2008; Tong et al., 2023). Heavy metal vapors at high temperatures can cause systemic toxicity, kidney and liver damage, and increase the risk of cancer, particularly from arsenic exposure (Khoshakhlagh et al., 2024). Extreme temperatures above 1200°C also cause heat stress, dehydration, and cardiovascular disorders, while poor ventilation increases the risk of carbon monoxide poisoning (Liu et al., 2022).

In addition to physical and chemical hazards, workers also face work stress due to production targets and the risk of accidents, which can impact mental health and productivity (Cendales et al., 2024). Furthermore, manual workloads and unergonomic working positions often lead to musculoskeletal disorders such as low back pain, muscle injuries, and joint deformities that can become permanent if left untreated (Soares et al., 2019).

Tin Refining and Heavy Metal Contamination

In the final stage of smelting, tin is purified through crystallization, utilizing differences in freezing points to separate impurities such as lead (Pb) and bismuth (Bi). While this method is effective, the process produces solid and liquid waste that still contains hazardous heavy metals, including Pb, Zn, As, and Cd (Zhou et al., 2023). Recent research shows that soil and sediments around tin smelting sites often contain heavy metals above environmental standards, with Cu, Cd, Pb, and Zn distributed into water bodies via surface runoff. These contaminants are persistent, readily accumulate in aquatic organisms, and enter the food chain, posing a risk to humans (Mosalem et al., 2024).

Heavy metal exposure has both acute and chronic impacts. Pb has been shown to impair children's cognitive development and increase the risk of hypertension, while arsenic from contaminated drinking water has been linked to skin, lung, and bladder cancer. Cadmium and Zn can damage the kidneys, disrupt calcium metabolism, and increase the risk of osteoporosis (Mititelu et al., 2025; Mitra et al., 2022). This situation emphasizes the need for a strict environmental monitoring system, adequate waste treatment technology, and public education on the dangers of heavy metals. Regular health check-ups are also crucial for early detection of toxic impacts. Therefore, a balance between industrial activities and public health protection is key to sustainable development (Briffa et al., 2020; Singh et al., 2023).

In addition to the public, smelter workers are also at high risk. Exposure to metal dust and direct contact with residues can cause anemia, kidney damage, neurological disorders, and cancer due to arsenic accumulation. Exposure to Cd and Bi causes respiratory irritation, chest pain, and liver damage (Jomova et al., 2025). Therefore, the use of PPE, proper ventilation systems, and regular health check-ups are essential to protect workers (Ada et al., 2025).

CONCLUSION

Tin mining has a significant impact on the environment, health, and occupational safety. Open-pit mining processes, both dry and wet, produce solid, liquid, and gaseous waste that pollutes the soil, water, and air, degrading ecosystem quality and increasing the risk of ecological disasters. Exposure to heavy metals such as Pb, As, and Cd is bioaccumulative and hazardous to public health, while mine workers face the risk of poisoning, lung disease, musculoskeletal disorders, and work stress. This situation emphasizes the need for proper waste management, the implementation of OHS standards, and continuous environmental and health monitoring. Therefore, a balance between industrial productivity and ecosystem protection is key to sustainable mining practices.

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