

The Extension Impact of Nickel Industry Activities in Weda Bay Central Halmahera, North Maluku, Indonesia

April 2025

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Acknowledgement

We want to thank all those who helped to develop and compile this research. This report presents new data on the impacts of nickel industry expansion in Weda Bay, Halmahera, North Maluku Province in Indonesia and recommends action steps by relevant stakeholders to protect workers and communities from related activities and the resulting pollution.

The research process received support from the Health Agency of Central Halmahera. The findings of this report were in consultation with the Health Agency and the Environmental Agency of Central Halmahera.

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Disclaimer

We would like to express their sincere gratitude for the financial and technical support received from various sources, making this document possible. The views and interpretations expressed herein should not be taken as reflecting the official opinions of any agencies that provide financial support. Nexus3 Foundation is solely responsible for the content.

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List of Abbreviations

AMDAL : *Analisis Dampak Lingkungan* / Environmental Impact Assessment

APBN : *Anggaran Pendapatan dan Belanja Negara* / State Budget

BOD_5 : Biochemical Oxygen Demand (5-days)

BPOM : *Badan Pengawas Obat dan Makanan* / Indonesian Food and Drug Supervisory Agency

COD : Chemical Oxygen Demand

CSQG : Canadian Sediment Quality Guidelines

DMO : Domestic Market Obligation

DO : Dissolved Oxygen

ERM : Environmental Resources Management

ESDM : *Energi dan Sumber Daya Mineral* / Energy and Mineral Resources

EV : Electric Vehicle

EWI : Estimated Weekly Intake

IARC : International Agency for Research on Cancer

IWIP : Indonesia Weda Bay Industrial Park

HAM : *Hak Asasi Manusia* / Basic Human Rights

HIV/AIDS : Human Immunodeficiency Virus/Acquired Immunodeficiency Syndrome

HPAL : High-Pressure Acid Leach

IEA : International Energy Agency

JECFA : Joint FAO/WHO Expert Committee on Food Additives

LME : London Metals Exchange

PLTU : *Pembangkit Listrik Tenaga Uap* / Coal-fired power plant

PLN : *Perusahaan Listrik Negara* / State-owned electric company

PTWI : Provisional Tolerable Weekly Intake

RCO : Research Center for Oceanography

RKEF : Rotary Kiln Electric Furnace

RPJMN : *Rencana Pembangunan Jangka Menengah Nasional* / National Medium Term Development Plan

SQG : Soil Quality Guidelines

THQ : Total Hazard Quotient

TOC : Total Organic Carbon

US EPA : United States Environmental Protection Agency

Foreword

As the global demand for electric vehicles and stainless steel continues to surge, the spotlight has intensified on the nickel mining and smelting industry, particularly in regions like Halmahera, North Maluku, Indonesia. This report aims to shed light on the extensive environmental and social impacts of nickel mining and smelter production in this region.

Halmahera, abundant in nickel deposits, has emerged as a vital player in the supply chain to satisfy the world's increasing demand for sustainable energy solutions. Nevertheless, this swift industrial expansion has serious consequences, including pollution and environmental degradation threatening the local ecosystem and communities.

In this report, we present updated insights and analyses of the impacts of nickel smelters, highlighting both the advantages and challenges of this vital industry. We aim to inform stakeholders about the complexities of nickel production and its implications, emphasising the necessity for responsible practices that balance economic growth with environmental stewardship.

We hope this report provides a valuable resource for policy-makers, industry leaders, and environmental advocates who must navigate the intricate dynamics of nickel mining and its far-reaching effects.

Sincerely,

Yuyun Ismawati

Co-founder and Senior Advisor of Nexus3 Foundation



Executive Summary

The shift to clean energy is increasing global demand for critical minerals like nickel, copper, cobalt, and lithium. Electric vehicles (EVs) and renewable energy infrastructure require significantly more mineral inputs than conventional technologies. Indonesia, with the world's largest nickel reserves and dominates global nickel production. The government banned raw nickel exports in 2020 to increase value-added benefits, leading to a surge in domestic smelting and processing investments. Nickel extraction relies on energy-intensive pyrometallurgical processes, mainly the Rotary Kiln Electric Furnace (RKEF) method. This process, widely used in Indonesia, generates high emissions, requiring coal-powered smelters that significantly contribute to pollution.

Central Halmahera, particularly Weda Bay, is a hotspot for nickel mining and processing. The Indonesia Weda Bay Industrial Park (IWIP) operates large-scale mining and smelting facilities. The area relies on coal-fired power plants, contradicting Indonesia's clean energy goals. Industrial expansion has led to land conflicts, loss of natural resources for Indigenous groups, and rising health concerns due to an influx of migrant workers and pollution-related diseases. The industry has spurred economic activity but also exacerbated land disputes, environmental degradation, and social tensions, particularly for local communities dependent on traditional livelihoods.

In July 2024, Nexus3, in partnership with the University of Tadulako, conducted a comprehensive primary data collection by testing and analyzing environmental and biological samples. These samples included sediment, water, fish, and blood from residents near the Weda Bay Area and the nickel mine. We also used secondary data from government agencies, prior research, and stakeholder interviews to enhance our findings.

Key Findings

- Our findings indicate that the **water quality in the Ake Jira area** has surpassed Class 1 water standards, rendering it **unsuitable** for drinking and other clean water uses by the community. A comparison with baseline data from 2008 further supports community complaints about the river's diminished function as a drinking and clean water source.
- The latest sediment tests indicate that the concentration of heavy metals in the river sediments is similar to the baseline data collected in 2007. This suggests that heavy metals may not accumulate significantly in these sediments. One possible reason is the river's current, which transports sediment from the upper reaches to the river mouth, where it is ultimately deposited into the sea. Given testimonies from fishermen and government officials regarding sedimentation at the river mouth, it is essential to conduct tests for heavy metal deposition in that area to assess the current environmental quality.
- All fish samples collected from Weda Bay contained **mercury** and **arsenic** at varying concentrations. According to Indonesian FDA regulations, four fish samples exceeded the maximum allowable limit for **total arsenic contamination of 2 mg/kg,** while seven samples contained arsenic levels within the range of 1-2 mg/kg. Additionally, none of the fish exceeded the maximum **mercury contamination** limit, including barracuda, which are classified as predator fish.
- An examination of **heavy metal concentrations in the blood** found that 22 individuals (47%) had mercury levels exceeding the safe limit of 9 µg/L. In comparison, 15 individuals (32%) had **arsenic levels surpassing the safe limit** of 12 µg/L out of 46 community respondents who participated in the study. **Blood levels of mercury and arsenic were higher in residents who were not workers at the IWIP.**

Recommendations

Environmental Aspect:

- Regular monitoring of water quality, sediments, and marine catch in Weda Bay is essential to track heavy metal contamination, particularly arsenic, mercury, nickel, and chromium. This monitoring should extend to river estuaries and surrounding waters near industry areas to ensure a comprehensive assessment of pollution sources and impacts.
- Transparent disclosure of environmental and health data to the public is crucial for informed decision-making and community awareness.
- Stricter emission limits for heavy metals from mining activities must be established and rigorously enforced to mitigate pollution. Violations should be met with firm penalties to ensure compliance.
- Law enforcement efforts must also be strengthened to regulate industrial waste, emissions, and pollution from nickel mining and processing industries, ensuring environmental protection and corporate accountability.
- Local governments and industries should provide air quality monitoring facilities that offer real-time information accessible to the public.

Health Aspect:

- Regular health check-ups, including blood tests for heavy metals, should be provided to communities near industrial areas to monitor and address potential health risks.
- Strengthening the capacity of district health facilities is crucial to ensure they can effectively manage the long-term impacts of heavy metal exposure, offering proper diagnosis, treatment, and preventive care.
- Public education on the dangers of consuming heavy-metals-contaminated seafood, particularly predatory species with high mercury levels, is essential to reduce health risks.
- Special attention should be given to vulnerable groups, such as pregnant women and infants, by promoting safer dietary choices to minimize heavy metal exposure and protect long-term public health.

This research is imperative for highlighting the serious concerns surrounding heavy metal pollution, particularly in regions near mining and processing industries. Such pollution poses a significant threat not only to the environment but also to the local community. Two major consequences of this pollution are the deterioration of environmental quality and the loss of biodiversity. Consuming contaminated food can have harmful effects on people's health. The lack of regular monitoring further intensifies these issues. Long-term exposure to heavy metals can lead to non-communicable diseases, which often act as a hidden threat, emerging only later in life, reducing the quality of life, and endangering future generations.




Google Maps
©2025
Kulo
Lelilef
Gemaf
Sagea
Weda Tengah District,
Central Halmahera Regency
Kobe
Gitaislam
Taseho
Weda
Tobaru

1 Background

1.1. Clean Energy Drives Critical Mineral Extractions

The clean energy system, a transformative force powered by technologies that convert natural resources into power, starkly contrasts the traditional fossil fuel-based system. It requires more minerals and promises a more sustainable future [1].

According to IEA (2022), a typical electric car requires six times the mineral inputs of a conventional vehicle, and an onshore wind plant requires nine times more mineral resources than a gas-fired power plant. Since 2010, the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as the share of renewables has risen.

The transition to a clean energy system is poised to position the energy sector as a significant force in mineral markets. Until the mid-2010s, the energy sector accounted for a small share of the total demand for most minerals. As the race for energy transition accelerates, clean energy technologies are emerging as the fastest-growing demand segment, highlighting the industry's impact.

To meet the Paris Agreement's goal, the total demand for clean energy technologies will rise significantly over the next two decades. The minerals and metals necessary for renewable energy, clean technology, and the transition to a more sustainable, low-carbon future are often called critical minerals [2]. Estimates suggest that over 40% of the demand will come from copper and rare earth elements, 60-70% from nickel and cobalt, and almost 90% from lithium [1].

Nickel (Ni) is a popular alloying element for stainless steel, used in 70% of the world's steel today [2,3,4]. Driven by urbanisation in emerging economies, its demand will continue to increase. Additionally, Ni is a key element in producing lithium-ion batteries, which are used by 5% of the world today and are necessary for electrifying the vehicle fleet [2,5].



Figure 1.1. IWIP Industrial Complex. (Photo: Andri Saputra)

1.2. Indonesia's Nickel Reserves

A handful of countries stand out globally regarding Ni's total imports and exports. Indonesia, the Philippines, and New Caledonia are the key players dominating the production and trade of laterite ore [4,6]. However, these countries retain low value-added from their operations; instead, Ni ores are mainly processed elsewhere in East Asia, such as Japan, Korea, and China [3,4,7].

Indonesia has the highest nickel deposits in the world, with around 23% of global reserves, with a total volume of 17.7 billion tons of ore, reserves of 5.2 billion tons of ore and 177.8 million tons of metal with reserves of 57 million tons [4,6]. In 2020, The Centre for Mineral, Coal, and Geothermal Resources Geological Agency Republic of Indonesia recorded that Indonesia's nickel ore reserves were about 1.1 billion tonnes, 722 million tonnes of which have a grade of ≤ 1.7% Ni and 363 million tonnes of > 1.7% Ni [8,9].

There are two main types of nickel, Class I and Class II. Class I nickel has a higher purity of 99.8% and is essential for electric batteries and London Metals Exchange (LME) deliverables. In contrast, Class II nickel has a purity of less than 99%, is non-LME deliverable, and is primarily used in stainless steel production. Nickel Class II is expected to face a significant supply surplus this year as production increases, particularly in Indonesia. Instead of supporting the ecosystem of electric vehicles in Indonesia, nickel processing primarily produces stainless steel [10].

According to the Germany Federal Institute for Geosciences and Natural Resources (BGR) calculations, Indonesia accounted for around 55 % of global nickel production in 2023 [11]. By the end of this decade, the country could even produce about 65 % of the worldwide supply.



Figure. 1.2. Nickel-processing capacity in operating, pre-production, and incentive facilities divided by region of production and ownership[1]. Source: Basuhi et al. (2024).[8]

[1] Ownership is assigned to the country of the private or state-owned entity with the most significant equity in the project. Data from S&P (2024) on processing facilities includes smelters, leaching plants, refineries, and sulfate plants. Pre-production is defined as projects where a go-ahead decision has been made and is being readied for production, including construction or commissioning stages. Incentive projects are defined here as either undergoing a scoping study or a feasibility study or having a completed feasibility study but not yet made a go-ahead decision. Processing facilities for the unreported development stage (2%–4% of total reported production) were not included.

Indonesia's role in the global nickel market is both dominant and exciting. As the world's largest producer of this crucial commodity, the nation's mining sector is buzzing with thrilling developments [4,6,12].

Chinese firms shifted to more abundant and inexpensive nickel from Indonesia instead of Russia [13], making Indonesia the largest nickel trade partner for China in terms of trade amount and value [7]. From a regional perspective, China mainly imported nickel raw materials from Southeast Asia and Oceania but exported final products to Europe and North America.

Since 2020, Indonesia has banned the export of raw nickel ore to encourage the downstream of the domestic nickel industry [14]. Exported nickel has a higher added value in processed products such as nickel matte and ferronickel (FeNi) [15]. In response to this export ban, many multinational companies have begun investing in constructing nickel processing and smelting facilities in Indonesia.

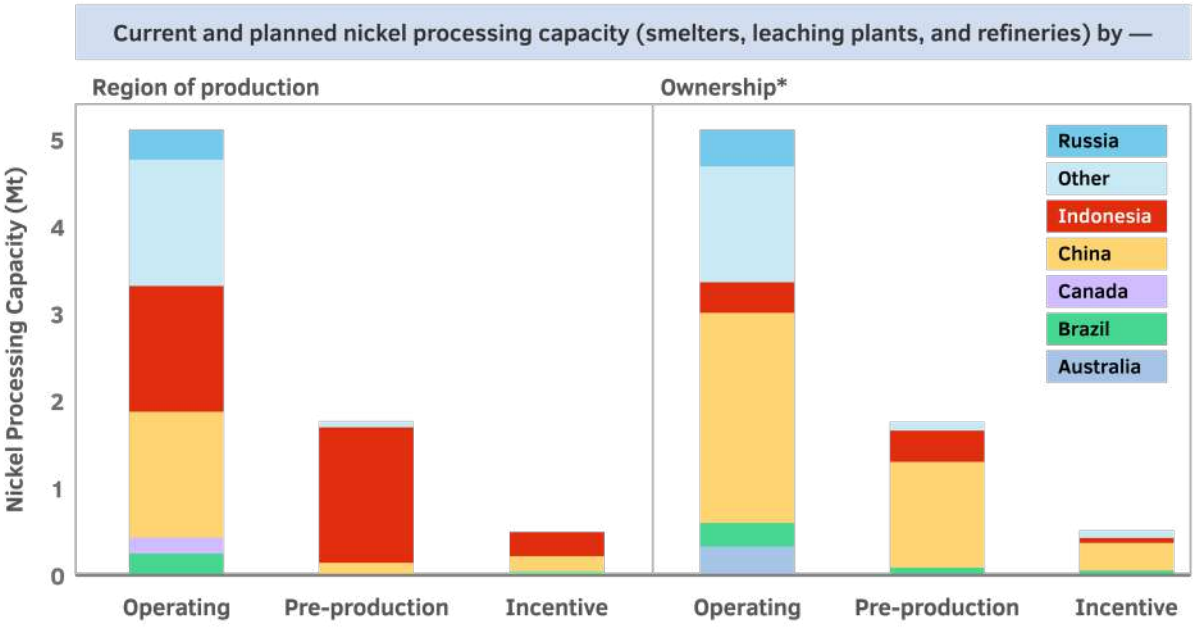


Figure. 1.3. Current and planned nickel processing capacity (smelters, leaching plants, and refineries) by Region of Production and Ownership. Source: Basuhi et al. (2024).[8]

The potential of nickel in Sulawesi and Halmahera islands in Indonesia is immense [12,16]. These islands are known for their largest nickel reserves, which promise various opportunities for the country's future. Depending on the situation, those Ni resources can be of multiple types, such as metallic nickel, ferronickel alloy, nickel matte, and nickel sulfate [20]. However, some experts and local communities consider them a resource curse and give insignificant benefits to the local communities [17,18,19,20].

1.3. Nickel Processing and Smelting Technology

Nickel is typically extracted from its ore using a combination of pyrometallurgy, hydrometallurgy, and electrometallurgy processes. The standard laterite pyrometallurgical flowsheet used in the last 50 years is generally called Rotary Kiln Electric Furnace (RKEF) [21].

Since 2020, the Indonesian government has prohibited the export of raw minerals and promoted added-value minerals through downstream policies and incentives [15,16]. This policy has increased investments and projects to build smelters nationwide [9,22]. Until 2024, 44 nickel smelters were built throughout Indonesia, and this number is predicted to grow [23].

However, pyrometallurgy has several disadvantages, such as energy-intensive and environmental impact. Pyrometallurgical processes can emit dioxins and furans and are not environmentally friendly [24,25].

To meet the energy needs and achieve high heat for pyrometallurgy technology, most nickel industrial areas and smelters are equipped with electricity supplied from coal-fired power plants (PLTU), which use coal specifically dedicated for industrial purposes (known as captive PLTU) [26]. One integrated nickel industry cluster could have ten captive coal-fired power plants.

The CREA and CELIOS studies showed that emissions from smelters and captive power in Central Sulawesi, Southeast Sulawesi, and North Maluku will leave an annual economic burden of USD 2.63 billion (IDR 40.7 trillion) in 2025 [19]. Furthermore, without meaningful interventions to mitigate emissions, this burden is expected to increase by more than 30%—or USD 3.42 billion (IDR 53 trillion)—in 2030.



Figure 1.4. Visible industrial emissions in IWIP, (Photo: Hariyanto Teng)

1.4. Nickel-related Policy and Regulatory Framework in Indonesia

In the 2025-2035 National Medium-Term Development Plan (RPJMN) [27], the nickel industry continues to be encouraged to support the national agenda in energy transition and the development of high-tech-based industries. The latest RPJMN also underlines the development of nickel-based industrial areas in Halmahera and Sulawesi. These areas will become centres for nickel mining, processing and developing derivative products, especially batteries.

The government is encouraging the construction of smelting facilities in both areas to reduce raw material exports and increase local economic benefits. The RPJMN also emphasises the importance of environmentally friendly mining practices, with strict supervision, to minimise negative impacts such as pollution and deforestation.

However, monitoring and prevention of pollution are not strictly implemented, resulting in many complaints and human rights violations regarding the right to a healthy life for communities and Indigenous Peoples around national strategic industrial areas [19,28,29].

Policy and regulations related to the nickel industry in Indonesia focus on the mining industry's environmental, health, safety, and governance aspects are listed below:

Law	Law Number 32 of 2009 concerning Environmental Protection and Management		Law Number 36 of 2009 concerning Health	Law Number 3 of 2020 about the Amandment of Law Number 4 of 2009 concerning Mineral and Coal Mining (Minerba Law)		Law Number 11 of 2020 concerning Job Creation	
Goverment Regulation	Government Regulation Number 41 of 1999 concerning Air Pollution Monitoring		Government Regulation Number 78 of 2010 concerning Reclamation and Postmining	Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management		Government Regulation Number 96 of 2021 concerning the Implementation of Mining Business Activities	
Presidential Regulation	Presidential Regulation Number 55 of 2019 concerning the Acceleration of the Battery-Based Electric Motor Vehicle Program for Road Transportation			Presidential Regulation Number 109 of 2020 concerning the Third Amendment to Presidential Regulation Number 3 of 2016 concerning the Acceleration of the Implementation of National Strategic Projects			
Ministerial Regulation	Regulation of the Coordinating Minister for Economic Affairs Number 7 of 2023 concerning the Third Amendment to the Regulation of the Coordinating Minister for Economic Affairs Number 7 of 2021 concerning Amendments to the List of National Strategic Projects	Regulation of the Minister of Energy and Mineral Resources Number 7 of 2020 concerning Procedures for Granting Areas, Licensing, and Reporting on Mineral and Coal Mining Business Activities	Regulation of the Minister of Energy and Mineral Resources Number 17 of 2020 concerning the Third Amendment to the Regulation of the Minister of Energy and Mineral Resources Number 25 of 2018 concerning Mineral and Coal Mining Business	Regulation of the Minister of Environment and Forestry Number 6 of 2021 concerning Procedures and Requirements for the Management of Hazardous and Toxic Waste	Regulation of the Minister of Environment and Forestry No. 5 of 2021 concerning Procedures for Issuing Approvals and Operational Feasibility Letters in the Field of Environmental Pollution Control	Regulation of the Minister of Environment and Forestry Number 16 of 2019 concerning The Second Amendment to Regulation of the Minister of Environment and Forestry Number 5 of 2014 concerning Wastewater Quality	Regulation of the Minister of Manpower Number 5 of 2018 concerning Ocuppational and Environmental Health and Safety
Ministerial Decree	Decree of the Minister of Energy and Mineral Resources Number 301.K/MB.01/MEM.B/2022 concerning the National Mineral and Coal Management Plan for 2022-2027			Decree of the Minister of Health of the Republic of Indonesia Number 1405/MENKES/SK/XI/2002 concerning Health Requirements for Office and Industrial Work Environments.			

Coordinating Minister for Economic Affairs
Ministry of Energy and Mineral Resources
Ministry of Environment
Ministry of Labour
Ministry of Health

Figure 1.5. Several laws and regulations related to accelerating the downstreaming of the nickel industry in Indonesia (source: data processed by researchers from various policy sources)

Regulations related to the nickel industry in Indonesia cover various aspects, from the environment and health to governance of the mining industry. One crucial regulation is Law Number 4 of 2009 concerning Mineral and Coal Mining, which regulates the rights and obligations of mining companies, including the obligation to manage the environment and reclaim land after mining.

Government Regulation Number 78 of 2010 also strengthened this regulation, which more explicitly regulates reclamation and post-mining to minimise environmental impacts. Nickel mining must also comply with the Regulation issued by the Ministry of Environment and Forestry (KLHK) regarding the Environmental Impact Analysis (AMDAL) mechanism, which must be carried out before a mining project begins to ensure that environmental and health impacts can be anticipated and controlled.



Figure 1.6. Nickel Smelters in IWIP (Photo: Andri Saputra)

In addition, air and water pollution are often the main issues in the nickel industry. Government Regulation Number 41 of 1999 concerning Air Pollution Control, and Regulation of the Minister of Environment and Forestry Number 16 of 2019 concerning the Second Amendment to Regulation of the Minister of Environment Number 5 of 2014 concerning Wastewater Quality Standards that mining companies must comply with.

This regulation aims to prevent pollution that can hurt the surrounding community's health. Applying more environmentally friendly technologies, such as tailings handling and waste processing, is also regulated not to pollute natural resources vital to the community.

In the context of public health, Law Number 36 of 2009 concerning Health emphasises companies' responsibility to maintain public health in their operational areas. Business actors must also provide compensation and health insurance for affected communities. Government supervision and community involvement in environmental management are regulated to minimise conflict and ensure that nickel industry activities adhere to sustainable principles and demonstrate high social responsibility.

1.5. Nickel Industry Situation in Central Halmahera, North Maluku

The total land area of Central Halmahera Regency is 2,276.83 km2, consisting of eight sub-districts. The wavy and undulating topography with lowlands includes Weda and Patani sub-districts in the eastern part of Halmahera Island.

In addition to Halmahera Island as its parent, the Central Halmahera Regency area consists of several islands, both inhabited and uninhabited. The number of islands in Central Halmahera Regency is approximately 43 islands, the largest of which is the Gebe Island group, which is inhabited. In contrast, the others are small islands (coral islands) [30].

The Central Halmahera Regency's physiographic conditions are formed by large reliefs where oceanic troughs and mountain ridges alternate strikingly. This area is part of the Melanesian continental environment. The soil and rock types reveal the region's geological conditions and soil structures. According to the geological map of Central Halmahera Regency (1992), most of the rock structures in the Region are composed of volcanic rocks.

Based on the soil type chart map of the Bogor Soil Research Institute in 1969 and the results of the basic data map of the development of the Central Halmahera Regency (1992), the type of soil found in the Central Halmahera Regency area is regosol soil. Regosol soil is suitable for planting media, agricultural irrigation, secondary crops, tobacco, and several types of fruits that do not require much water.

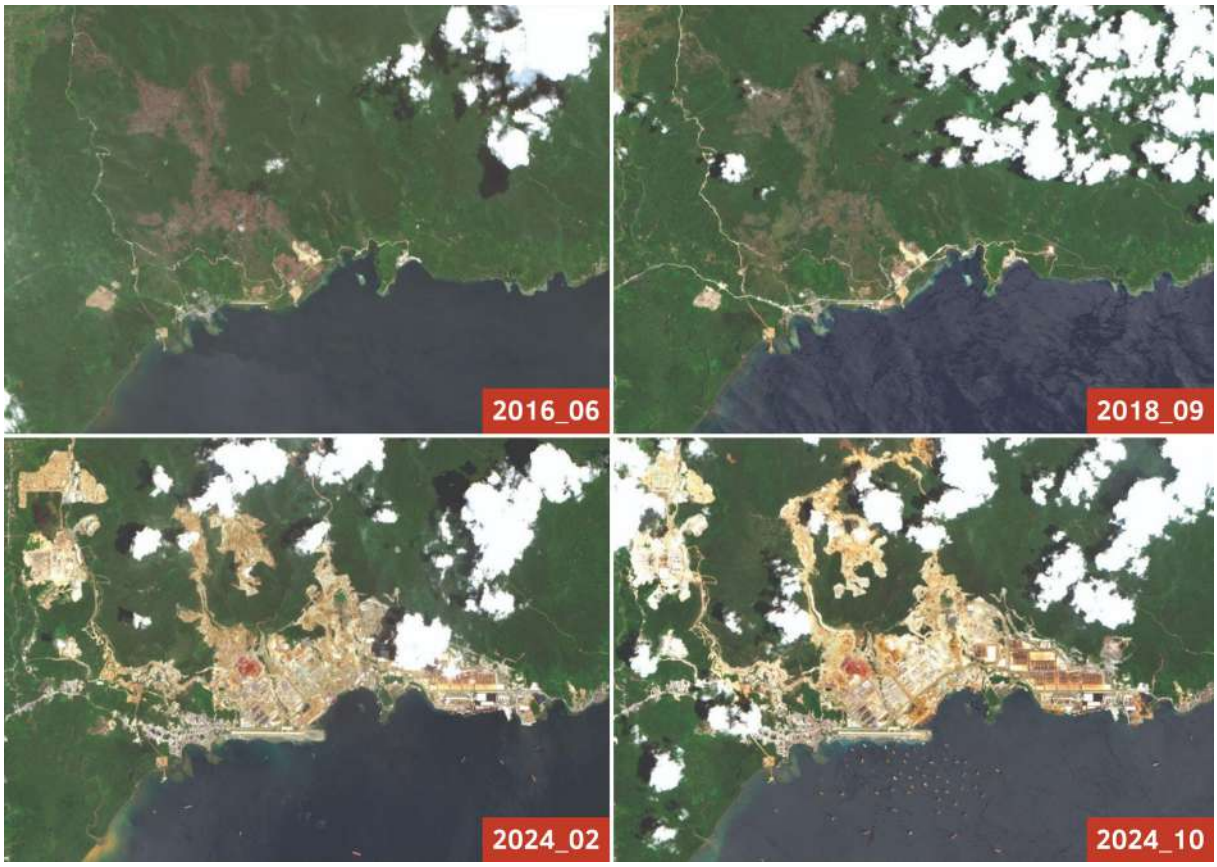


Figure 1.7. Weda Bay area before and after the establishment of IWIP from 2016 to 2024. (source: Sentinel-2/Copernicus Dataspace)

North Maluku has the most extensive nickel resources in Indonesia. One area that continues to be encouraged for nickel production in Central Halmahera is the Weda Bay area. The Weda Bay Industrial Park is a nickel mining and industrial park complex in Central Halmahera Regency, North Maluku, Indonesia. The Weda Bay Mine is now among the largest nickel mines in the world [31].

The Weda Bay Nickel mine, located in Central Halmahera and East Halmahera, North Maluku, has been operating since 2019. This nickel mine is operated by PT Weda Bay Nickel (WBN), which is majority-owned by the Chinese company Tsingshan (51.3%) and the French company Eramet (37.8%). The Indonesian government owns the remainder through PT Aneka Tambang Tbk. (Antam) at 10%. Eramet contributes its expertise in mining operations, while Tsingshan operates nickel processing and refining facilities.

The Indonesia Weda Bay Industrial Park (IWIP) is the centre of nickel mining and processing activities in Indonesia [32]. IWIP is an integrated mineral industrial area investment from three Chinese companies: Tsingshan Holding Group, Huayou Cobalt, and Zhenshi Holding Group. At least four to five companies, including Weda Bay Nickel (WBN), operate nickel mines and smelters in IWIP. Several subcontractor and service provider companies support mining activities.



Figure 1.8. Industrial activity in IWIP, (Photo: Hariyanto Teng)

In the IWIP area, 11 captive Steam Power Plants (PLTU) are already operating, and three more are scheduled to be completed by the end of 2024. The total energy generated from the 14 captive PLTUs in the IWIP area is around 3.78 Gigawatts/year to 4.5 Gigawatts/year [33]. However, even though the steam technology used is supercritical, using low-quality coal as an energy source causes environmental pollution, especially air pollution around Weda Bay [19]. This is at odds with Indonesia's ideals towards a clean energy transition.

Unsustainable mining affects several areas in East and Central Halmahera. In Central Halmahera, the Weda Tengah and Weda Utara Districts are areas of concentration for nickel mining and its derivative industries. For many years, the nickel industry in Weda Bay has had significant economic and environmental impacts on Halmahera Island. The media additionally reported various industrial accident cases, especially in the nickel smelters unit and floods in the settlement.

The population of Central Halmahera as of mid-2022 was 59,096, but in mid-2023, the population increased rapidly to 96,977 persons, mainly due to the nickel industry job opportunities [30]. The number of workers in 2024 will continue to increase, reaching as many as 47,000, considering the massive demand for nickel in the coming years. Many are migrant workers outside North Maluku, such as Sulawesi and Java. Some also come from local communities in Halmahera.

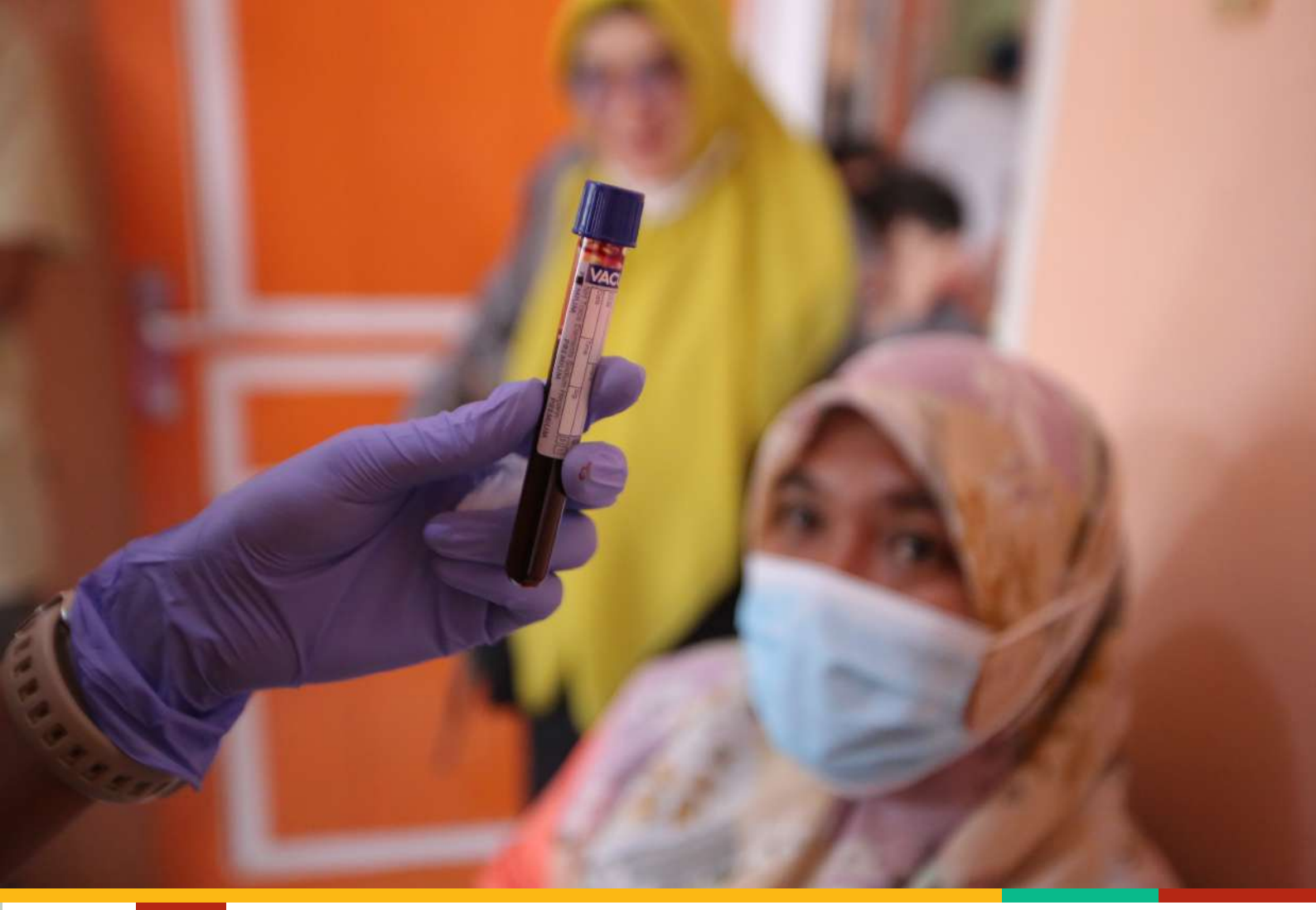


Figure 1.9. Fishing communities at the crossroads of nickel industry expansion, (Photo: Hariyanto Teng)

In addition to these ripple effects, the nickel industry has rip-off effects, including a psychosocial impact on the community, mainly when land conflicts arise and access to natural resources is lost [21,31,34]. This is especially true for Indigenous groups, who rely on the surrounding nature and land for their livelihoods [35].

Information circulated in news outlets and social media platforms also highlighted the significant influx of migrant workers, over 10,000, primarily from China, joining the workforce in Halmahera. As the industrial area expands and becomes populated with migrant workers, communicable diseases and noncommunicable diseases, such as HIV/AIDS and respiratory issues, are also on the rise [19,34,35].





2 Methodology and Sampling

2.1. Methodology

The study team collected primary data by testing and analysing environmental and biological samples, including sediment, water, fish, and blood samples from people living near IWIP and the nickel mine, as the potential pollution hotspots. They utilised secondary data from government agencies or previous studies and conducted interviews with relevant sources to support the existing findings.

2.2. Sampling

2.2.1. Environmental Samples

In July 2024, river sediment and water samples were collected from several locations around the Weda Bay area and one site in the Sagea River. The selection of sampling points considered the distance from the industrial site, which is potentially affected by pollutants from mining or nickel industry activities.

Heavy metal testing in river sediments is crucial for detecting anthropogenic pollutant sources in aquatic environments. Furthermore, heavy metal accumulation in sediments can be a secondary source of water pollution when environmental conditions shift. Water and river sediments interact synergistically, providing valuable pollution correlation information within the water body. Heavy metals that enter the river through waste disposal or runoff from mining activities exist in various forms.

Heavy metals typically exist in water bodies as dissolved ions, which can be deposited into the sediment under certain conditions (such as changes in pH, salinity, and other parameters). Heavy metals in sediments, including those naturally present in the sediment's composition, can be remobilised when disturbed, such as during dredging with heavy equipment or stirring from rain. The biological activity of microorganisms also enhances the dynamics of river pollutant changes.



Figure 2.1. Sampling location in Ake Jira River (Photo: Andri Saputra)

River water quality testing is carried out by looking at the potential for organic and inorganic pollutant pollution. Organic pollutants in water bodies can be detected by testing the Total Organic Carbon (TOC), which calculates the total carbon contained in organic pollutants; Biochemical Oxygen Demand (BOD_5), which measures the presence of organic compounds by calculating the amount of oxygen consumed by decomposing microorganisms; Chemical Oxygen Demand (COD), which is the amount of oxygen needed to oxidise organic substances in water; and Dissolved Oxygen (DO), which is calculating the amount of dissolved oxygen in water. Meanwhile, inorganic pollutants are metal ions, sulfates, phosphates, nitrates, and others with high bioavailability.

Oxygen is vital for maintaining aquatic environmental life, but it can decrease in quantity when water bodies are contaminated with organic compounds. When organic compounds are abundant in water, aquatic microorganisms automatically work to decompose them, requiring a lot of oxygen to do so. When the amount of oxygen in water bodies decreases due to this phenomenon, fish are usually found dead floating on the water's surface.

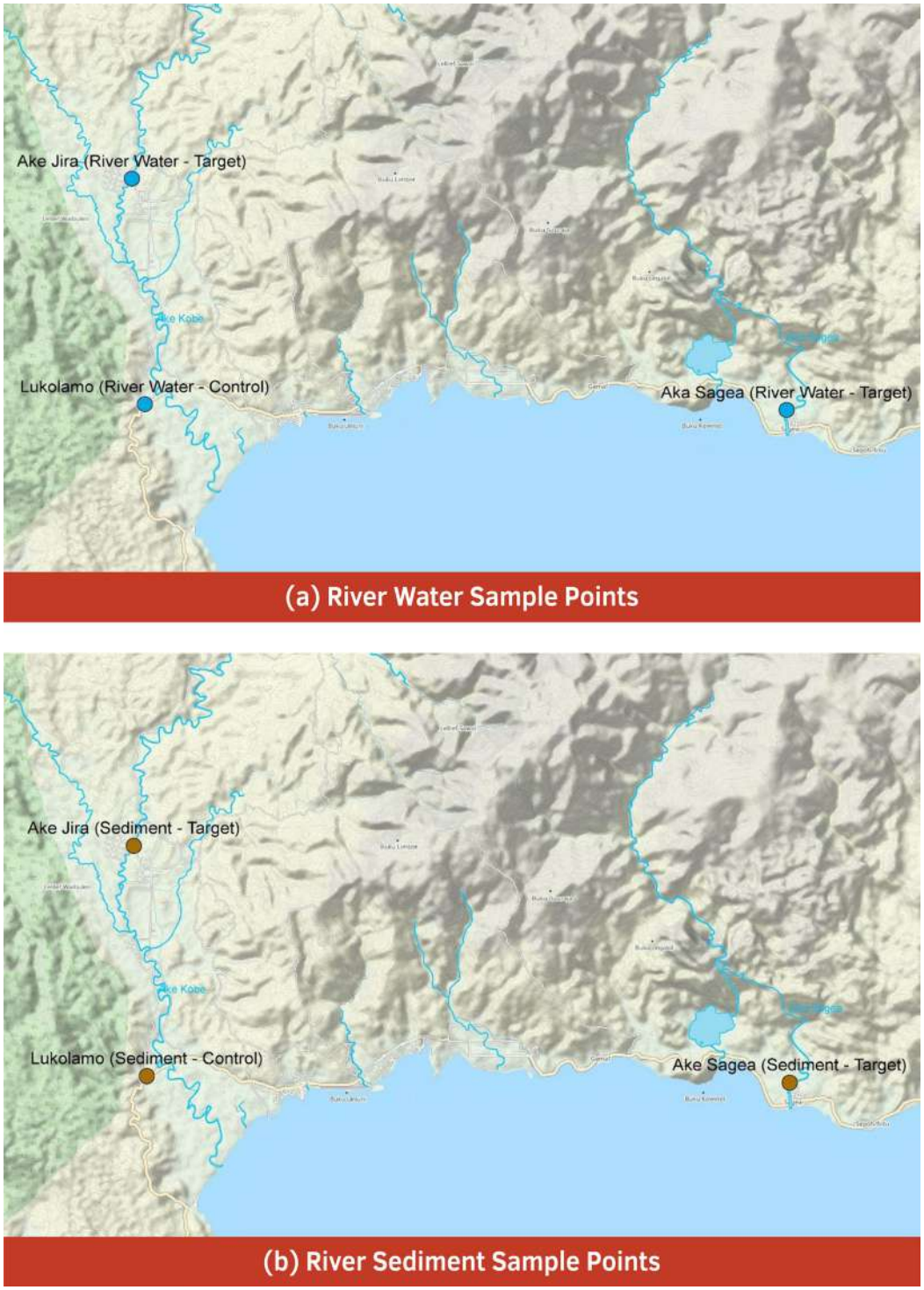


Figure 2.2. Environmental sampling points in this study. (source: Sentinel-2/Copernicus Dataspace)

Water samples collection

Three river water samples were collected and testesxxd for several parameters, namely Total Organic Carbon (TOC), Biochemical Oxygen Demand (BOD_5), and Chemical Oxygen Demand (COD), along with Dissolved Oxygen, to see indications of organic pollutants and several heavy metals, namely total Mercury (Hg), Nickel (Ni), Cadmium (Cd), Chromium (Cr), Arsenic (As), with the addition of Hexavalent Chromium (Cr^{6+}).

Water samples were placed in a one-litre jerry can, conditioned at pH 2 using nitric acid (HNO3), and stored in cold temperatures until delivery to the laboratory. They were then placed in 500 mL dark glass bottles for TOC analysis. Samples were analysed in three accredited laboratories: Saraswati Indo Genetech, Makassar Public Health Laboratory Center, and Tadulako University Integrated Laboratory.



Figure 2.3. Water sampling activity in Lukulamo River, (Photo: Hariyanto Teng)

Sediment samples collection

Three river sediment samples were collected and analysed for eight heavy metal parameters: total Mercury (Hg), Nickel (Ni), Cadmium (Cd), Chromium (Cr), Arsenic (As), Lead (Pb), Iron (Fe), and Cobalt (Co).

Sediment was collected from three points using PVC pipes at a 5-10 cm depth. It was homogenised in a plastic basin by stirring twice using the quarter method, placed into polyethene ziplock bags, and stored at low temperatures until delivery to the laboratory. Samples were analysed in an accredited laboratory, Saraswati Indo Genetech, using an ICP-MS (Inductively Coupled Plasma-Mass Spectrometer) and an ICP-OES (Inductively Coupled Plasma-Optical Emission Spectrometer).

2.2.2. Human Biomonitoring

To examine the broad impact of pollution around Weda Bay, we conducted biomonitoring by analysing six heavy metal levels in residents' blood. The total number of respondents was 61– 46 people living in the two villages closest to IWIP, Gemaf Village and Lelilef Village, and 15 from Ternate, who acted as a control group.

Blood sampling was conducted on July 6, 2024, at the Lelilef Health Center, Lelilef Village and on July 7, 2024, at the Gemaf Assistant Health Center, Gemaf Village. Respondents in the target group were divided into two categories, workers and non-workers, with "workers" defined as people who work at IWIP.

The Medical and Health Research Ethics Committee, Faculty of Medicine, Tadulako University, issued the Ethics Clearance Letter No. 2117/UN 28.1.30/KL/2023.

Table 2.1. Number of respondents for biomarkers monitoring

Village name	Blood samples collected	IWIP workers respondents	Non-workers respondents
Gemaf	23	12	11
Lelilef	23	14	9
Control	15	-	15
Total	**61**	**26**	**35**



Figure 2.4. Blood sampling points in this study (source: Sentinel-2/Copernicus Dataspace)

Analysts from PRODIA Ternate carried out blood sampling, which was analysed at the accredited PRODIA Central Laboratory in Jakarta. We utilised the "Toxic Panel" package provided by PRODIA, which includes examining As, Cd, Pb, Hg, Ni, and Tl (Thallium) levels in the blood. Whole blood samples were used to analyse As, Cd, Pb, Hg, and Tl, while serum samples were employed to analyse Ni.

In addition to blood sampling by the analyst, a general health examination is also conducted by the local doctors. Respondents also completed the questionnaire interviews and answered questions about their current and historical health problems and food intake during the last 48 hours. Potential environmental exposures that might be considered confounding factors were also discussed with respondents. Additional examinations related to occupational exposure to chemicals and materials in the workplace, such as coal, nickel ore, and industrial waste (e.g., fly ash, bottom ash, and nickel slag), were also recorded during the interview.



Figure 2.5. (a) Respondents participating in health survey, (b) Blood sample collection, (c) Blood sample for analysis, (Photo: Andri Saputra)

2.2.3. Marine Fish Samples

Fresh fish samples were purchased from fishermen's houses in Gemaf Village and the traditional fish market in Lelilef Village. We bought fish unloaded from Gemaf's fishermen's boats, which had just anchored when they returned from the sea. All fish sampled in this study were caught from the waters of Weda Bay, see Figure 2.6.

The total number of fish samples was 16, nine from Gemaf fishermen and seven from the Lelilef traditional market. The types of fish were selected randomly according to the fish stock availability on 8 July 2024. The limited time available was an obstacle to finding more fish and other marine biota, such as shellfish from the waters of Weda Bay, which had been planned initially.



Figure 2.6. Fish sampling points in this study (source: Sentinel-2/Copernicus Dataspace)



Figure 2.7. Potential Fishing Grounds of Halmahera Fishermen Communities (source: Bing Satellite/SAS Planet)

The purchased fish are weighed whole, measured for length and width, filleted, separated from bones and skin, and then 50-100 grams of fillet meat are taken. The fillet meat is placed in vacuum plastic, sealed, and stored in an ice box. Samples are sent to an accredited laboratory, Saraswati Indo Genetech (SIG) in Jakarta, for comprehensive analysis of heavy metals, including Hg, Ni, Pb, Cd, Co, Cr, and As, using ICP-MS (Inductively Coupled Plasma-Mass Spectrometry) and ICP-OES (Inductively Coupled Plasma-Optical Emission Spectrometry).



Figure 2.8. (a) Fish Sampling activity and (b) Sampled fish for analysis (Photo: Hariyanto Teng)

2.3. Human Risk Assessment

2.3.1. Heavy Metals Risks in Biomarkers

Biomonitoring of heavy metals is conducted to provide exposure information and, if possible, health risk assessments or evaluate public health status[36]. The decline in environmental quality due to elevated pollution levels negatively impacts living organisms, including humans, directly and indirectly. Pollutants in our surroundings, whether in water, air, or food, enter our bodies through the respiratory tract, food contact, and skin exposure. Generally, our bodies can regulate these foreign compounds through detoxification processes. However, frequent exposure can surpass the body's detoxification capacity, resulting in harmful effects from these compounds. Moreover, the concentration and type of pollutants also influence the body's detoxification response.

Just as testing pollutant concentrations in biota helps determine pollution levels in an area, humans, as inhabitants of the environment, can also be subjects for measuring pollutant concentrations to evaluate the extent of pollution's harmful effects on health. Analysing pollutant levels in biota aims to highlight the potential risks pollution poses to humans. Exposure to heavy metals can negatively impact the human body and damage various organs. Unfortunately, few studies monitor heavy metals in populations living near industrial areas.

2.3.2. Potential Sources of Heavy Metals in the Blood of Teluk Weda Community

Human biomonitoring of heavy metals typically relies on urine and blood samples to assess short-term exposure to a compound, usually within the last 1 or 2 days. On the other hand, long-term exposure is evaluated through hair and nail samples over a range of years. Blood samples indicate a person's acute or recent exposure to a compound, while urine samples are utilised to detect chronic exposure that persists for a more extended period.

Arsenic, cadmium, lead, and mercury are systemic toxicants that can induce adverse effects in humans, including cardiovascular disease, neurological disorders, cancer, and immune disorders. Lead, cadmium, and arsenic can destroy cells by contributing to the formation of reactive oxygen species.

Several studies have found that exposure to heavy metals can cause long-term health problems [37,38,39].Some metals' acute and chronic effects have been known, but information related to the health impacts of combined heavy metals is still minimal.

Many factors influence exposure to and the effects of heavy metals on the body. Higher exposure to heavy metals in men is generally associated with lifestyle, occupation, history of smoking and alcohol consumption, and high blood hematocrit values (some heavy metals are bound to erythrocytes). In general, an individual's age, gender, medical history, and nutritional status affect the absorption of heavy metals in the body and the effects they cause.

2.3.3. Heavy Metals Content in Fish Consumed by Residents

The data from the analysis of total heavy metals (Hg, Pb, Cd, Cr, As, Ni, and Co) in fish fillet meat were then used to calculate the Estimated Weekly Intake (EWI) and Total Hazard Quotient (THQ).

EWI provides information on the risk of exposure to heavy metals in food to humans by comparing estimated consumption in a week with a safe limit that can be tolerated (Provisional Tolerable Weekly Intake/PTWI). THQ assesses the estimated potential non-cancer health risks that arise from exposure to a pollutant through food [40,41,42].

Estimated Weekly Intake (EWI)

EWI calculation uses the following equation [43]:

$$EWI = \frac{mean\ heavy\ metal\ concentration\ in\ fish\ muscle\left(\frac{mg}{kg} wetweight\right) x\ weekly\ fish\ consumption(kg)}{bodyweight(kg)}$$

According to data from the Indonesian Ministry of Maritime Affairs and Fisheries, the average consumption value of fresh fish in Indonesia is 57.27 kg/capita/year [44]. According to a US EPA study on fish consumption, fishermen generally consume an average of 49-50 kg annually, or the equivalent of 136.9 g/person/day [45,46].

Based on this information and supported by research questionnaire data on respondents' seafood consumption trends, the average consumption value of fresh fish is assumed to be 100 g/person/day, equivalent to 0.7kg/week. The average adult body weight used is 60 kg [47].

The results of the EWI calculation in mg/kg units were converted into µg/kg and compared with the Provisional Tolerable Weekly Intake (PTWI) value of each heavy metal, which is 7 µg/kg for Cadmium (Cd), 25 µg/kg for Lead (Pb), 15 µg/kg for inorganic Arsenic (As) [48], 4 µg/kg for Mercury (Hg) [49], 637 µg/kg for Chromium (Cr) [50], and 35 µg/kg for Nickel (Ni) [51,52,53].

The JECFA (Joint FAO/WHO Expert Committee on Food Additives) did not set the PTWI value of cobalt (Co) [54]. In 2011, JECFA revoked the PTWI value of inorganic Arsenic, 15 µg/kg, because it was considered insufficiently protective [55]. Since a replacement value was not set, this study still uses Arsenic's 15 µg/kg value.

Total Hazard Quotient (THQ)

The Total Hazard Quotient or THQ calculation uses the following equation [56,57]:

$$THQ = \frac{EFxEDxIRxC}{RDxBWxAT} x10^{-3}$$

Where:

EF (Exposure Frequency) is 365 days per year;

ED (Exposure Duration) is 70 years, according to the average lifespan of Indonesian people;

IR (Ingestion Rate) is 100 grams of fish per day;

C is the concentration of heavy metals in fish fillet meat (mg/kg);

BW is body weight in kg (assuming 60 kg is used);

AT (Average Exposure Time) or average exposure time is the average duration of consumption of the food (EF x 70 years); and

RD (Reference Dose) is the oral reference dose.

The reference dose is the amount of daily exposure to a hazardous compound that does not cause adverse effects on an individual. The oral RD used was 0.003 mg/kg/day for Cr, 0.02 mg/kg/day for Ni, 0.0004 mg/kg/day for Pb, 0.0003 mg/kg/day for Hg [57], 0.001 mg/kg/day for Cd, and 0.0003 mg/kg/day for As [46,58]. No oral RD value for Co has been established, so the THQ value of Co cannot be calculated [59].



Figure 2.9. Continuous emissions occur day and night from coal power plants in the communities of Gemaf and Lelilef. (Photo: Hariyanto Teng)



3 Results and Discussions

3.1. Environmental Samples

3.1.1. River Sediment Quality

There are three river sediment sampling points. The sample coded HLH-001, collected from a small river along the road where people wash their motorbikes and clothes and bathe in the Lukolamo area, is a comparison/control sample presumed to be free from heavy metal pollution. Meanwhile, two other river sediment samples were collected from targeted rivers, Ake Jira and Ake Sagea.

On the sampling day, Weda was still experiencing the rainy season, resulting in high water discharge and strong currents in the Ake Jira River. The river water appeared brownish-orange, resembling the colour of the sediment taken from the riverbank. In the upstream section of the river, extensive land clearing for nickel mining is evident. In contrast, Ake Sagea appears greenish with black sediment and has a humus-like odour.

Table 3.1. Heavy metals analysis in sediment samples (in mg/kg)

Sample ID	Location	Hg	Ni	Pb	Fe	Cd	Co	Cr	As
HLH-002 (Target)	Ake Jira	ND	2,096.10	ND	46.70	0.04	131.54	534.43	ND
SAGEA-001 (Target)	Ake Sagea	ND	1,226.13	ND	31.94	0.02	62.32	384.72	ND
HLH-001 (Control)	Lukolamo	ND	5.45	ND	14.62	0.06	7.18	4.02	ND

The concentration of several heavy metals in the two target river sediment samples showed very high values compared to the comparative sediment samples. The Ake Jira River sediment had a Ni metal content of 2,096.1 mg/kg, Fe of 46.68 mg/kg, Cd of 0.04 mg/kg, Co of 131.54 mg/kg, and Cr of 534.43. The Ake Sagea river sediment had a Ni metal content of 1,226.13 mg/kg, Fe of 31.93 mg/kg, Cd of 0.02 mg/kg, Co of 62.32 mg/kg, and Cr of 384.72. The analysis instrument did not detect Hg, As, and Pb metals in the three sediment samples.

The flow of water from the mining area in the upstream section of the river may contribute to the elevated concentrations of Ni, Cr, and Co in the sediments of both rivers. However, this assertion must be substantiated by comparing the heavy metal measurements in this study with those of river sediments before the onset of large-scale mining activities.



Figure 3.1. Collecting river water sediment in Sagea, (Photo: Hariyanto Teng)

3.1.1.1. River Sediment Analysis

The analysis of heavy metals in the sediments is compared with the quality standards established by the US EPA and the Canadian Sediment Quality Guidelines (CSQG) for the protection of aquatic life, as Indonesia currently has no sediment quality standards.

Based on Soil Quality Guidelines (SQG) by the US EPA

The Soil Quality Guidelines (SQG) proposed by the USEPA establish quality standards indicating heavy metal contamination in sediment [60]. Upon comparing three river sediment samples against the USEPA sediment quality standards, the concentrations of four heavy metals were categorised as "Unpolluted". However, the concentrations of Cr and Ni in the Ake Jira and Ake Sagea Rivers sediments exceeded the USEPA sediment quality standards, placing them in the "Heavily polluted" category.

Table 3.2. Comparison of the sediment samples based on USEPA Soil Quality Guidelines

Parameters	US EPA Soil Quality Guidelines Categories			Nexus3's Results 2024		
	Not polluted (in mg/kg)	Mildly polluted (in mg/kg)	Heavily polluted (in mg/kg)	HLH-001 (Lukolamo)	HLH-002 (Ake Jira)	SAGEA-001 (Ake Sagea)
Hg	-	-	-	ND	ND	ND
Ni	<20	20-50	>50	5.45	2096.1	1226.13
Pb	<40	40-60	>60	ND	ND	ND
Fe	<17000	17000-25000	>25000	14.621	46.699	31.940
Cd	-	-	>6	0.06	0.04	0.02
Co	-	-	-	7.18	131.54	62.32
Cr (total)	<25	25-75	>75	4.023	534.432	384.724
As	<3	3-8	>8	ND	ND	ND

Based on Canadian Sediment Quality Guidelines (CSQG) for Aquatic Life

The Canadian Council of Ministers of the Environment (CCME) has established the Canadian Sediment Quality Guidelines (CSQG) for Aquatic Life to protect the aquatic environment from pollution. In these guidelines, Canada uses threshold effect levels (TELs), termed Interim Sediment Quality Guidelines (ISQGs), and probable effect levels (PELs) [61].

This guideline provides an overview of the potential toxicity of heavy metals in sediments to the aquatic environment by evaluating the level of adverse biological effects on organisms [62]. The following table compares the analysis results with the CCME quality standards.

Table 3.3 Comparison of the sediment samples with Canadian Sediment Quality Guidelines (CSQG) for Aquatic Life

Parameters	Canadian Sediment Quality Guidelines (CSQG) for Aquatic Life		Nexus3's Results 2024		
	TEL value (mg/kg)*	PEL value (mg/kg)*	HLH-001 (Lukolamo)	HLH-002 (Ake Jira)	SAGEA-001 (Ake Sagea)
Hg	0.17	0.486	ND	ND	ND
Ni	-	-	5.45	2096.1	1226.13
Pb	35	91.3	ND	ND	ND
Fe	-	-	14.6214	46.6988	31.9395
Cd	0.6	3.5	0.06	0.04	0.02
Co	-	-	7.18	131.54	62.32
Cr (total)	37.3	90	4.023	534.432	384.7239
As	5.9	17	ND	ND	ND

* The data used refers to the Guidelines values for the 1997-1998 period, which are available on the website https://ccme.ca/en/summary-table

The interpretation of these two-value constants is as follows

x	**:**	**Heavy metal concentration in the test sample**
x < TEL	**:**	**Minimum Effect Range, where adverse effects are infrequent/do not occur**
TEL < x < PEL	**:**	**Medium Effect Range, where adverse effects sometimes occur**
x > PEL	**:**	**High Effect Range, where adverse effects often occur**



Of the eight heavy metals analysed, Canada has sediment quality standards for only Hg, Pb, Cd, Cr, and As, while there is no data available for Ni, Fe, and Co. Based on the available data, the results of the heavy metal analysis in sediment samples indicated that the concentration of Cd did not exceed the TEL value. In contrast, the total concentration of Cr was above the PEL quality standard in two sediment samples. Sediment samples from Ake Jira exhibited a Cr concentration six times higher than the Probable Effect Levels (PEL).

In comparison, samples from Ake Sagea showed a Cr concentration 4.3 times above the PEL value. The elevated levels of Cr in sediments from Ake Jira and Ake Sagea fall within the range where adverse effects on aquatic organisms may frequently occur.

Conclusions about whether metals sedimentated on the riverbed have harmed aquatic organisms living in the river cannot be drawn quickly. Further testing is needed, such as determining the bioavailability of these metals or conducting benthic organism testing [63]. However, testing heavy metals in these sediments is sufficient to provide information regarding high concentrations of heavy metals in rivers that can potentially harm the aquatic environment.

3.1.2. River Water Quality

The inorganic parameters tested were the total concentration of heavy metals Hg, Ni, Cd, As, and Cr^{6+} ions. The organic parameters tested were TOC, BOD_5, COD, and DO. The results of the water sample testing are shown in the following table.

Table 3.4. The results of water sample testing

Sample ID	Location	Inorganic Pollution Parameters						Organic Pollution Parameters			
		Hg *(µg/L)*	Ni *(mg/L)*	Cd *(mg/L)*	Cr^{6+} *(mg/L)*	Cr *(mg/L)*	As *(mg/L)*	TOC	BOD_5	COD	DO
HLH-002 (Target)	Ake Jira	0.031	0.268	0.02	<0.01	0.03	ND	1.9	4.33	12.3	7.25
SAGEA-001 (Target)	Ake Sagea	ND	0.02	ND	ND	0.01	ND	-	-	-	-
HLH-001 (Control)	Lukolamo	0.026	ND	0.01	<0.01	ND	ND	1.26	0.57	1.41	7.8

The three river waters exhibited very low Hg, Ni, Cd, Cr, and Cr^{6+} concentrations, with As metal remaining undetected. In the Sagea River water, no Hg, Cd, Cr^{6+}, or As metals were detected or were present below the instrument detection limit. Meanwhile, several heavy metals, including Hg, Cd, Cr, Ni, and Cr^{6+}, were found in the Ake Jira River water sample, albeit at low levels.



Figure 3.2. Ake Jira river during water and sediment sampling, (Photo: Andri Saputra)

3.1.2.1. River Water Analysis

The parameters for detecting organic pollution were only for Lukolamo and Ake Jira River water samples. The analysis results were compared with the river water quality standards and similar standards in Appendix VI of Government Regulation (GR) No. 22 of 2021, as shown in the following Table.

Table 3.5. Comparison of the river water with Indonesian Water Quality Standards

No.	Parameters	Unit	Appendix VI of GR No. 22 of 2021		Nexus3's Results 2024	
			Class III	Class I	HLH-001 (Lukolamo)	HLH-002 (Ake Jira)
1	BOD_5	mg/L	6	2	0.57	4.33
2	COD	mg/L	40	10	1.41	12.3
3	DO	mg/L	3 (minimum threshold)	6 (minimum threshold	7.8	7.25
4	Hexavalent Chromium	mg/L	0.05	0.05	<0.01	<0.01

The four parameters are still within safe limits when referring to the Class 3 quality standard, so it can be concluded that there is no pollution from organic pollutants in the water of the Ake Jira River.

The analysis results were compared with the river water quality standards of Class 1 and Class 3. Class 1 was used because the Ake Jira River was a drinking and clean water source for the community before the nickel mining and processing industry operated massively. Only four parameters from the regulation can be compared with the analysis results, namely BOD_5, COD, DO, and Hexavalent Chromium (Cr^{6+}), due to the limitations of the test parameters carried out.

In Appendix VI of Government Regulation No. 22 of 2021, the information on the concentration of heavy metals required is the concentration of dissolved heavy metals, so it cannot be compared objectively with the results of the total heavy metal testing that has been carried out.

3.1.3. River Sediment and Water Results Comparison based on Location

Data analysis on the presence of heavy metals from 3 sample points in sediment and water is summarised in Table 3.6.

Table 3.6. Sediment and water samples analysis

Parameter	Control		Target			
	HLH-001 (Lukolamo)		HLH-002 (Ake Jira)		SAGEA-001 (Ake Sagea)	
	Sediment (in mg/kg)	Water (in mg/L)*	Sediment (in mg/kg)	Water (in mg/L)*	Sediment (in mg/kg)	Water (in mg/L)*
Hg	ND	0.026 µg/L	ND	0.031 µg/L	ND	ND
Ni	5.45	ND	2096.1	0.268 mg/L	1,226.13	0.02 mg/L
Pb	ND	-	ND	-	ND	-
Fe	14.62	-	46.69	-	31.93	-
Cd	0.06	0.01 mg/L	0.04	0.02 mg/L	0.02	ND
Co	7.18	-	131.54	-	62.32	-
Cr (total)	4.02	ND	534.43	0.03 mg/L	384.72	0.01 mg/L
Cr^{6+}	-	<0.01 mg/L	-	<0.01 mg/L	-	ND
As	ND	ND	ND	ND	ND	ND

*except for Hg, in ug/L

Mercury and cadmium were detected in the water at low concentrations in a small river in the Lukolamo area. The sediment from this river also contains Nickel, Iron, Cadmium, Cobalt, and Chromium at low concentrations. This point is a control/comparison point because of its remote location and the lack of pollution from mining or industrial activities.

The orange-brownish water of Ake Jira contained mercury, nickel, cadmium, and chromium. Meanwhile, the sediment includes nickel, iron, cadmium, cobalt, and chromium. Iron minerals may be responsible for the orange colour of the river water. The concentrations of nickel, iron, cobalt, and chromium in the sediment are significantly higher compared to the control sample. The heavy metal profile in this sediment resembles that of the sediment sample from Ake Sagea. The water from the Sagea River showed no traces of the heavy metals tested, except for chromium at a very low concentration.

Overall, the analysis results show that mercury was only detected in water media, and arsenic metal was not detected in sediment or water. Nickel is the metal with the highest concentration in sediments, followed by chromium, cobalt, and iron. The highest concentration of these four metals was found in the Ake Jira sediments—nickel, cobalt, iron, and chromium form nickel laterite ore [62].

3.1.4. River Sediment and Water Samples Results Comparison with 2007 Baseline Data

3.1.4.1. River Water Samples

Environmental Resources Management (ERM), a multinational consulting firm focused on the environment and sustainability, conducted sediment and water quality checks on several rivers within the Weda Bay Nickel (WBN) concession area from 2007-2008.

The document "Eramet-PT Weda Bay Nickel Exploration and Development ESIA" [31] compares the river water quality with Government Regulation No. 28 of 2001 concerning Water Quality Management and Water Pollution Control. This regulation was no longer valid when revoked in 2021 and replaced by Government Regulation No. 22 of 2021.

ERM tested the water quality at Ake Jira at three points: upstream, middle, and downstream of the river and Ake Sagea at the upstream and downstream. Fortunately, our sampling point in Ake Jira almost overlapped with AJIRA2 (middle stream) sample code taken by ERM, making the comparison more comparable.

The following table compares the water quality of Ake Jira in 2024 with that in 2008, taking into account the limitations of the test parameters in this study.

Table 3.7 Comparison of Ake Jira water quality samples between 2008 and 2024

No.	Parameter	Unit	GR No. 82 Year 2001 (Class 1)	Eramet 2008*			Nexus3 2024
				Ake Jira (Downstream) (1)	Ake Jira (Mid-stream) (2)	Ake Jira (Upstream) (3)	Ake Jira (Mid-stream)
1	BOD_5	mg/L	2	< 2	< 2	< 2	4.33
2	COD	mg/L	10	8	< 2	< 2	12.3
3	DO	mg/L	6 (minimum threshold)	7.7	8.4	7.7	7.25
4	Hexavalent Chromium	mg/L	0.05	<0.002	0.003	0.003	<0.01

*Note: * Eramet-PT Weda Bay Nickel Exploration and Development ESIA, Environmental Resources Management (ERM)*
(1) Sample code: AJIRA1; (2) Sample code: AJIRA2; (3) Sample code: AJIRA3

The water quality of the Ake Jira River in 2008, taken between July 31 and August 1, was still within safe limits when referring to the Class 1 quality standards of GR No. 82 of 2001. Although this Government Regulation is no longer in effect, the quality standard values set are the same as the Class 1 quality standards written in Attachment VI of GR No. 22 of 2021. ERM uses Class 1 criteria because river water is used as drinking

and clean water (bathing, washing, toilets) when water samples are taken. On the day of sampling, the condition of the river water was reported to be clear with low turbidity even though it was raining and cloudy.

The water quality of the Ake Jira River, based on the 2024 test based on COD and BOD_5 parameters, exceeds the Class 1 river water quality standards. Reflecting on field conditions, where the river water is now orange with high turbidity visually, the Ake Jira River is no longer suitable for use as drinking water and clean water by the community. This comparison confirms community complaints regarding the loss of the river's function as a drinking and clean water source.

3.1.4.2. River Sediment Samples

In July-August 2007, ERM tested 13 sediment samples from 10 rivers included in the Weda Bay Nickel area with parameters of Arsenic, Cadmium, Chromium, Cobalt, Copper, Lead, Mercury, Nickel, Zinc, Selenium, Silver, and Barium. Sediment from Ake Sagea was taken from two points, namely upstream and downstream. There is no detailed explanation regarding the concentration of heavy metals per sample and only a narrative explanation in the form of a range.

Based on testing in 2007, Ake Sagea sediment contained arsenic concentrations of 10 mg/kg, chromium of 406 mg/kg, cobalt above 50 mg/kg, lead below 50 mg/kg, mercury below 0.5 mg/kg, and nickel above 500 mg/kg. Other metals, such as zinc, calcium, and copper, were also detected, but their concentrations were not reported. Table 3.8. compares the results of heavy metal testing in sediment from 2024.

Table 3.8 Comparison of heavy metals in sediment between 2007 and 2024 (in mg/kg)

Year	Location	Hg	Ni	Pb	Fe	Cd	Co	Cr	As
2007 by Eramet	Ake Sagea	< 0.5	> 500	<50	-	detected	> 50	406	10
2024 by Nexus3	Ake Sagea	ND	1,226.13	ND	31.94	0.02	62.32	384.72	ND

The latest sediment tests show that the concentration of heavy metals is not much different from the tests conducted by ERM 17 years ago. Hearing many reports from the public regarding pollution of the Sagea River, which is suspected to be due to run-off from land clearing for mining in the upper reaches of the river, coupled with a study conducted by Weda Bay Nickel where the Sagea River flows into the company's concession area, this data provides information that heavy metals do not accumulate much in river sediments.

One reason may be the river current, which carries sediment from the upper reaches to the mouth of the river, ultimately depositing it in the sea. Fishermen have reported that sedimentation often occurs at the river mouth, producing shallower water. In an interview with Mongabay, Syamsul Bahri Ismail, Former Head of the Central Halmahera Environmental Service, stated in 2022 that sedimentation has occurred repeatedly [64]. Therefore, testing for heavy metal deposition at the river mouth is necessary to evaluate the current environmental quality.

3.2. Marine Fish Samples and Risk to Human Consumption

Sixteen marine fish were tested for heavy metal parameters. The types of fish were selected randomly based on availability on the sampling day to provide information on heavy metal exposure in fish consumed by people living in Weda Bay. Arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and mercury (Hg) are heavy metals that pose a threat to public health due to their toxicity. These metals are systemic toxicants that can cause organ damage even at low exposure levels.

According to the US EPA and the International Agency for Research on Cancer (IARC), these metals are categorised as “known” or “likely” carcinogens in humans [65,66]. Meanwhile, nickel and cobalt are considered essential metals for the body. Chromium is also necessary for bodily functions but can have adverse effects at high levels. The results of the total heavy metal concentrations in various fish species are presented in Table 3.9., alongside the fish species caught.

Table 3.9 The results of the total heavy metal concentrations in various fish species and the fish species caught.

Bought from	Fish name	Type of fish	No. of sample	Average concentration (in mg/kg)		Estimated Weekly Intake (in µg/kg)	
				Hg	As	Hg	As
Gemaf fisherman’s catch	Barracuda *(Sphyraena barracuda)*	Large pelagic fish	1	0.28	0.83	3.26	9.68
	Gutila *(Lethrinus laticaudis)*	Large pelagic fish	2	0.07	0.79	0.87	9.21
	Gurara *(Lutjanus vitta)*		3	0.04	1.91	0.54	22.32
	Sorihi or Ikan Layang *(Decapterus koheru)*		1	0.11	3.03	1.28	35.38
	Kembung *(Rastrelliger kanagurta)*	Large pelagic fish	1	0.04	0.65	0.46	7.58
	Ciongo		1	ND*	1.16	-	13.53
Lelilef traditional market	Dolosi *(Caesio cuning)*		3	0.03	0.90	0.38	10.53
	Somasi		1	0.04	2.73	0.46	31.85
	Sorihi or Ikan Layang *(Decapterus koheru)*		3	0.04	1.77	0.50	20.72
Provisional Tolerable Weekly Intake (PTWI)						**4**	**15.00**

* ND = Not Detected

Testing of total heavy metal levels in fish taken from Weda Bay showed that fish muscle was confirmed to contain heavy metals. Mercury (Hg) and arsenic (As) were found in every fish tested, Nickel (Ni) was detected in one of the gutila fish at a level of 0.25 mg/kg, Cadmium (Cd) was detected in one of the dolosi fish at a concentration of 0.02 mg/kg, and Chromium (Cr) was detected in the same gutila fish and sorihi fish at concentrations of 0.57 mg/kg and 0.30 mg/kg. Lead (Pb) and Cobalt (Co) were not detected in all fish samples, with the detection limit of the ICP-MS device used is 0.002 mg/kg for Pb and 0.001 mg/kg for Co.



Figure 3.3. A Gemaf fisherman is returning home after fishing far away. (Photo: Hariyanto Teng)

Heavy metals not detected in fish meat may accumulate in other body parts. Chromium is generally found in the gills, kidneys, and liver; it rarely accumulates in fish meat. Water's acidity (pH) significantly affects chromium's bioavailability and its accumulation in fish. Several studies have shown that lead is found more in the gills and liver [65,67,68]. Heavy metals accumulate in functional organs, such as the gills and liver, because the liver detoxifies foreign compounds that enter the fish's body. The gills are the entry point for seawater into the fish's body.

Mercury concentrations in fish range from 0.02-0.28 mg/kg (ppm), with the highest concentration in barracuda. Arsenic concentrations in fish range from 0.43-3.03 mg/kg (ppm), with the highest concentration in sorihi fish caught by Gemaf fishermen at 3.03 ppm. Three sorihi fish purchased from the Lelilef traditional market had an arsenic concentration range of 1.02-2.47 mg/kg with an average of 1.77 mg/kg.

3.2.1. Fish Samples Results Comparison with 2007 Baseline Data

In 2007, the Research Center for Oceanography (RCO - LIPI) was appointed by Weda Bay Nickel to conduct heavy metal checks on marine fish meat consumed by the community in Weda Bay for baseline data in ANDAL [31]. Seventeen marine fish samples were tested for 11 heavy metal parameters, including seven heavy metal parameters tested by the Nexus3 study.

Table 3.10. Heavy metals content in Fish samples from RCO-LIPI data 2007 (source: Research Center for Oceanography - LIPI, 2007)

Heavy metals content in Fish samples from RCO-LIPI data 2007	
Parameter	**Concentration (in mg/kg)**
Pb	< 0.010
Cd	0.004-0.041
Cr	0.006-0.023
Ni	0.131-0.311
Co	0.002-0.044
Hg	0.005-0.192
As	0.001-0.021

Based on the existing baseline data, the concentration of arsenic in fish meat in Weda Bay in 2024 increased rapidly, with the lowest finding being 20 times higher than in 2007. The concentration of Hg did not differ much from the baseline data. The lowest concentration of Cr detected among the two fish samples was 13 times higher than the highest concentration of Cr in the baseline data. The concentration of Cd detected in 1 sample was still within the baseline data range, as was the concentration of Ni. Pb remained undetected in fish samples in 2024. Cobalt was not detected in all samples, even though the baseline data indicated otherwise.

3.2.2 Safe Limits of Heavy Metals Contaminants in Food

Many international institutions and Indonesian Food and Drug Administration (FDA) have set safe limits for metal contamination in seafood. These values are pretty diverse, and there are different considerations for each issuing institution. There is no binding uniformity for classifying seafood products. Still, many regulations agree to differentiate the maximum limit values for top predatory fish, such as tuna, mackerel, shark, etc., from non-predatory fish. A compilation of maximum limit values (Maximum Limit, ML) is presented in Table 3.11.

Table 3.11. Permissible Maximum Limit (ML) for heavy metals in fishery products (source: data processed by researchers from various regulation sources)

Regulation	Products	Pb	Hg	As	Cd	Cr	Ni
European Commission Regulation No.1881/2006	Muscle meat of fish	0.3 mg/kg ww	0.5 mg/ kg ww (for tuna, sardine, marlin, rays, dogfish, shark, swordfish, redfish, eel, mackerel, and some other fish is 1 mg/ kg)		0.05 mg/kg ww (for tuna, sardine, eel, mackerel is 0.1 mg/kg; swordfish 0.3 mg/kg)		
	Bivalve molluscs	1.5 mg/kg ww	1 mg/kg ww		1 mg/kg ww		
	Crustaceans	0.5 mg/kg ww	0.5 mg/kg ww		0.5 mg/kg ww		
Indonesian FDA Regulation No.5 Year 2018 (*withdrawn*)	Fish and Fishery Products Including Molluscs, Crustaceans and Echinoderms as well as Amphibians and Reptiles	0.2 mg/ kg, (except processed predator fish such as swordfish, tuna, marlin 0.4 mg/ kg)	0.5 mg/ kg, (except processed predator fish such as swordfish, tuna, marlin 1 mg/kg)	0.25 mg/kg	0.1 mg/ kg, (except processed predator fish such as swordfish, tuna, marlin 0.3 mg/kg)		
	Seaweed	0.2 mg/kg	0.03 mg/kg	0.15 mg/ kg, (except for Nori and Dry Seaweed 1 mg/kg as inorganic arsenic)	0.05 mg/kg		
Indonesian FDA Regulation No. 9 Year 2022 (*replacement of Indonesian FDA Regulation No. 5 Year 2018*)	Processed fish products	0.3 mg/ kg, (except processed fish including cephalopods or shellfish 1 mg/ kg)	0.5 mg/ kg, (except processed predator fish such as swordfish, tuna, marlin 1 mg/kg)	2 mg/ kg (Arsen total)	0.3 mg/ kg, (except processed fish including cephalopods or shellfish 1 mg/kg)		
	Seaweed	0.2 mg/kg	0.03 mg/kg	1 mg/kg, as inorganic arsenic	0.05 mg/kg		
FAO recommendations in Tahnan et al. 2022 [69]	Seafood					12 mg/kg	70 mg/kg

Regulation	Products	Pb	Hg	As	Cd	Cr	Ni
Food and Agriculture Organization, No. 66/2003	Edible parts of fishery products	0.2 mg/kg fresh weight (for wedge sole, eel, spotted seabass, horse mackerel or scad, grey mullet, sardine, grunt, and common two-banded seabream are 0.4 mg/kg fresh weight)	0.5 mg/kg fresh weight (for rays, shark, atlantic catfish, and other fish listed, mostly predators, are 1 mg/kg fresh weight)		0.05 mg/kg fresh weight (for wedge sole, eel, horse mackerel or Scad, grey mullet, sardine, european anchovy, luvar, and common two-banded seabream are 0.1 mg/kg fresh weight)		
	Crustaceans	0.5 mg/kg fresh weight			0.5 mg/kg fresh weight		
	Bivalve molluscs and cephalopods	1 mg/kg fresh weight			1 mg/kg fresh weight		
US FDA in Tahnan et al. 2022 [69]	seafood					13 mg/kg	80 mg/kg
JECFA, Codex Alimentarius, with latest revision in 2023	Fish	0.3 mg/kg					
	Marine bivalve molluscs				2 mg/kg (not applicable to oyster and scallop)		
	Cephalopods				2 mg/kg (applies to cuttlefishes, octopuses, and squids without viscera)		

Indonesian FDA Regulation allows only five heavy metal contaminants in food and beverages. In addition to the four listed in the table, tin (Sn) is regulated. For processed fish and seaweed products, Indonesian FDA has updated the maximum contamination limit values for several heavy metals, such as the arsenic limit in fish, which has been changed to 2 mg/kg total arsenic from 0.25 mg/kg, and the arsenic limit in seaweed from 0.15 mg/kg to 1 mg/kg inorganic arsenic.

Several international regulations, including JECFA and the European Commission, do not establish a maximum limit for arsenic contamination in fish or other processed seafood products. Regarding mercury, nearly all international and domestic regulations agree on a threshold of 0.5 mg/kg for fish or processed fish products, except for predatory fish, which is set at 1 mg/kg.

According to Indonesian FDA Regulation, four fish samples exceeded the maximum arsenic contamination limit of 2 mg/kg total arsenic, while seven fish samples fell within the range of 1-2 mg/kg. The four samples include two sorihi fish, one gurara fish, and one somasi fish. Additionally, no fish exceed the maximum mercury contamination limit, including barracuda fish, which belong to the predator category.

3.2.3. Risks of Contaminated Fish Consumption in Communities

Heavy metals can be toxic to the human body if someone is continuously exposed to high-frequency levels and exceeds the safe consumption limit. Calculating the estimated daily intake (Estimated Daily Intake/ EDI) or estimated weekly intake (EWI) of a compound/ pollutant in food is necessary to determine the level of exposure to the compound/ pollutant. The Food and Agriculture Organization and the World Health Organization, or through the Joint FAO/WHO Expert Committee on Food Additives (JECFA), have set a safe limit for weekly consumption of a compound/pollutant in food called the Provisional Tolerable Weekly Intake (PTWI).

Calculating the estimated daily intake (EWI) of mercury and arsenic in 16 fish samples showed that seven fish samples exceeded the safe weekly intake (PTWI) of arsenic of 15 ug/kg. The range of arsenic EWI values from the samples was 7.58 - 35.38 ug/kg, averaging 17.32 ug/kg. The highest arsenic EWI values were found in sorihi samples from Gemaf and Lelilef and gurara fish. The mercury EWI values were 0.35 - 3.26 ug/kg, with an average of 0.77 ug/kg.



Figure 3. Fish Survey in Lelilef Local Market (Photo: Hariyanto Teng)

All samples were still below the mercury PTWI value of 4 ug/kg. However, the barracuda fish caught by Gemaf fishermen weighing 250 grams had an EWI value close to the

PTWI value of 3.26 ug/kg. Suppose predatory fish of that size are near the safe limit for weekly mercury consumption. In that case, predatory fish of larger sizes, including tuna, may accumulate more mercury and increase the risk of weekly consumption by the community [70].

Based on the estimated potential non-cancer health risks calculation, the Target Hazard Quotient (THQ) value of mercury is 0.18 - 1.55. All THQ mercury values fall into the range of THQ <1, where non-cancer health risks are not predicted to occur, except in the barracuda sample with a mercury concentration of 0.28 mg/kg.

The barracuda sample's mercury THQ value is 1.55; if it is higher than 1, there may be non-cancer health risks. Although the EWI value of mercury from the barracuda sample does not exceed the PTWI for mercury, there is a potential for non-cancer health risks based on the THQ calculation.

3.3. Human Biomonitoring — Heavy Metals Levels in Blood Samples of Weda Bay's Communities

The examination of heavy metal concentrations in the blood revealed that 22 individuals (47%) had mercury levels exceeding the safe limit of 9 µg/L. In comparison, 15 individuals (32%) had arsenic levels surpassing the safe limit of 12 µg/L out of 46 community respondents who participated.

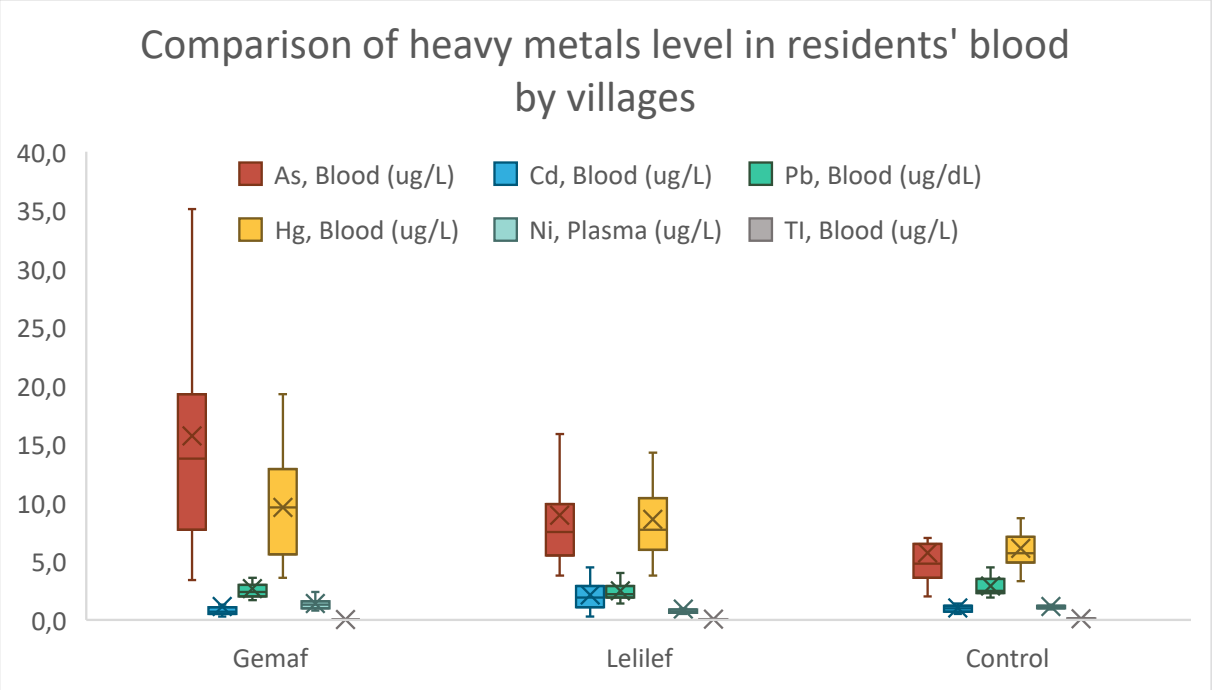


Figure 3.4. Comparison of heavy metals level in blood of respondents in this study.

The Gemaf Village community had 12 cases of arsenic and 13 cases of mercury in their blood samples, surpassing the safe limit for 23 individuals, with nine showing both instances. The arsenic concentration in the blood of the 12 cases ranged from 13.2 to 43.7 µg/L, with an average of 22.94 µg/L. The mercury concentration values in the 13 cases varied from 9.6 to 19.3 µg/L, with an average of 12.66 µg/L. Based on the interview results, individuals with both cases consumed seafood approximately 2-3 times daily. The average seafood consumption in 2 days before blood sampling was 2-6 servings.

The Lelilef Village sample recorded 3 cases of arsenic and 9 cases of mercury in the blood, exceeding the safe limit from a total sample population of 23 individuals, with only one person showing both instances. The arsenic concentration values for the 3 cases ranged from 15.9 to 27.2 µg/L, with an average of 20.76 µg/L. The mercury concentration values for the 9 cases were 10 and 14.3 µg/L, with an average of 11.9 µg/L. The seafood consumption pattern was approximately 2 to 3 times per day, and each individual had a history of consuming seafood within 2 days before having blood samples taken.

The concentrations of nickel, thallium, lead, and cadmium in the blood of 46 individuals were below the safe limit value. Figure 3.5. compares the results of heavy metal testing in blood per village.

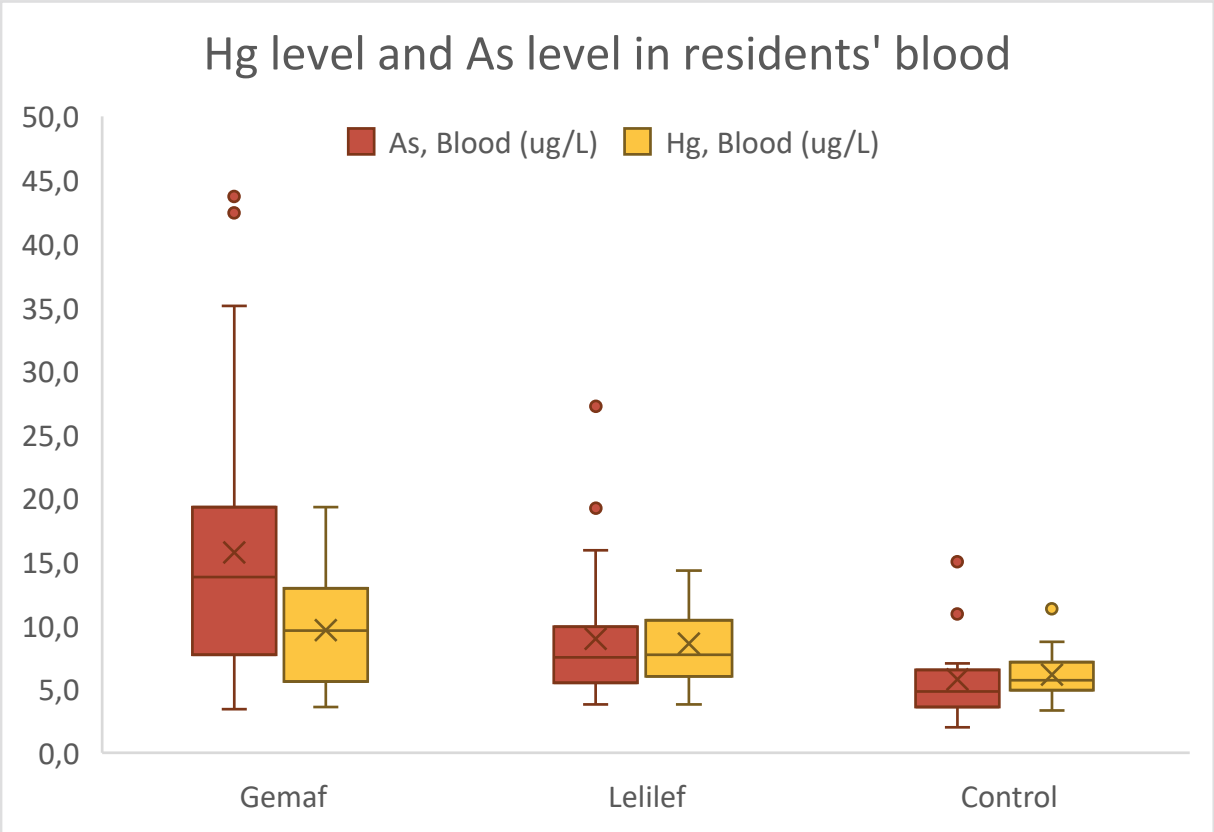


Figure 3.5. Mercury and arsenic levels in residents' blood

Overall, residents of Gemaf Village had higher average blood levels of arsenic and mercury than those in Lelilef Village and the control group.

Nickel levels in the blood of Gemaf Village residents were higher than those of Lelilef Village residents, yet they remained well below the safe limit. Lead levels in the blood of residents from both villages were comparable.

At the same time, the average cadmium level in residents' blood in Lelilef Village was 1.75 times higher than that of Gemaf Village, though it remained below the safe limit.

Thallium levels in the blood were also higher in residents of Lelilef Village, but they were still far below the safe limit. Figure 3.6. compares heavy metal levels in the blood of residents of Gemaf Village and Lelilef Village.



Figure 3. Blood Sampling Process by Laboratory Analyst (Photo: Hariyanto Teng)

What's Thallium?

Thallium is a heavy metal known to cause a broad spectrum of adverse effects in humans, and its compounds are poisonous [71]. It is found in trace amounts in the Earth's crust, typically associated with sulfide ores of other metals like zinc, copper, iron, and lead [72]. Thallium emissions into the environment typically originate from coal combustion and smelting processes, as thallium is a trace contaminant in raw materials. Due to its high acute toxicity on living organisms, the ecotoxicological importance of thallium is comparable to lead and mercury [73].

Thallium has also been detected in fly ash from coal-fired power plants, with concentrations ranging from 29 to 76 µg/g, increasing as particle size decreases. Thallium is released into water primarily from mining, iron and steel manufacturing, non-ferrous metal production, and ore processing through leaching (EPA 1980a, 1983c; Ewers 1988). Meanwhile, releases into soil are predominantly associated with solid waste from coal combustion and smelting operations (Ewers 1988) [74].

When thallium enters the human body, it is absorbed and distributed rapidly to various organs, particularly the kidneys and liver. This compound has a slow excretion rate. High levels of thallium exposure over a short period can affect the nervous system, lungs, heart, liver, and kidneys. However, there is currently no available information on the health effects of long-term exposure to low levels of thallium [75].

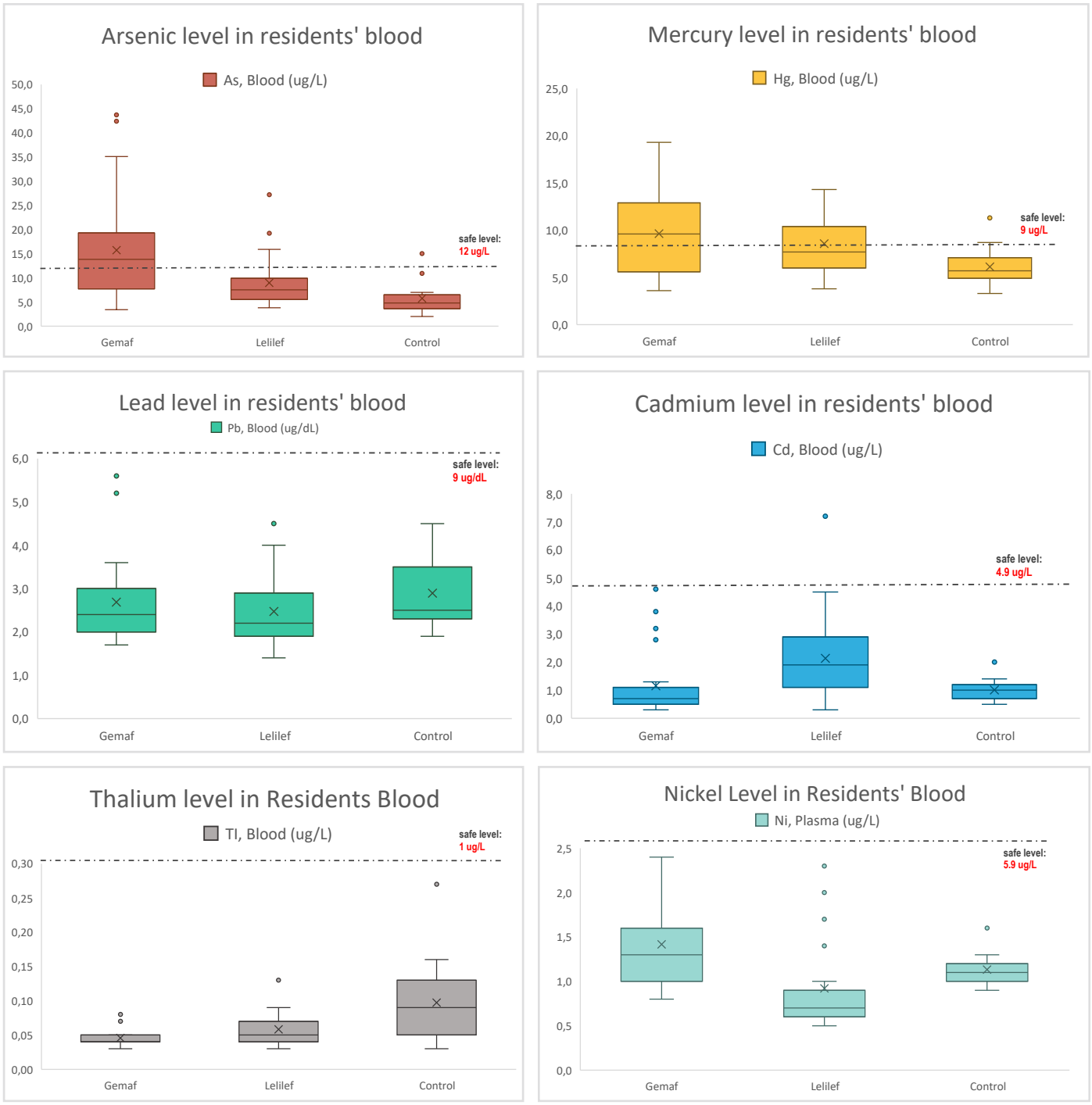
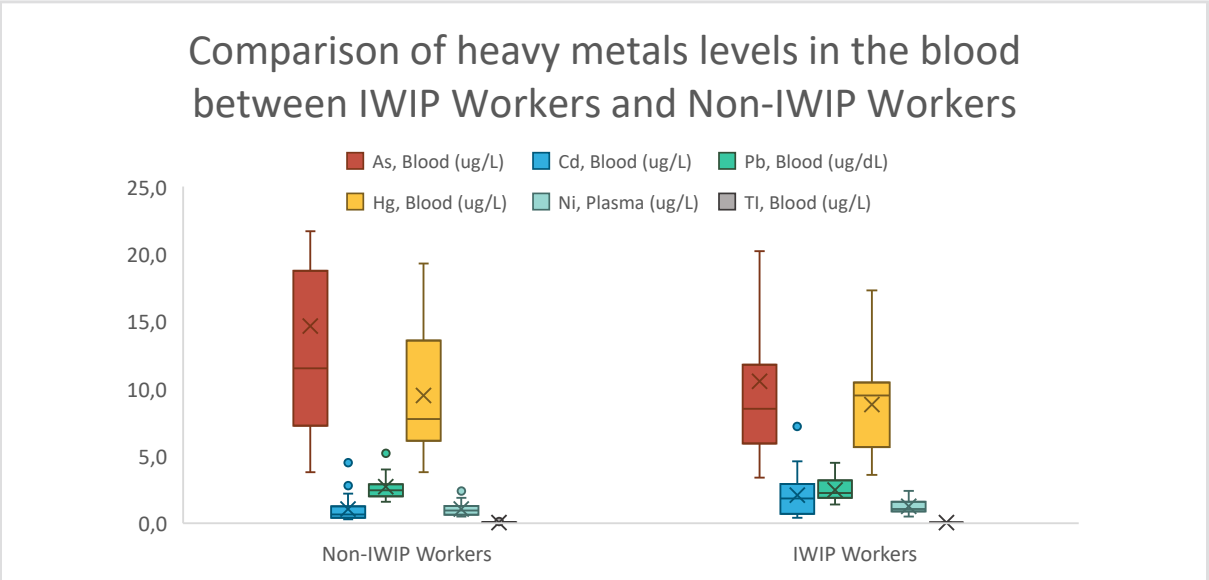


Figure 3.6. Comparison of heavy metal levels in the blood of community respondents with safe limit value derived from PRODIA

3.3.1. Heavy Metals Levels in Blood Samples of IWIP Workers vs Non-IWIP Workers

Sources of heavy metal exposure arise from both environmental and occupational origins. To determine the primary source of exposure, we analysed the distribution of heavy metal levels in the blood based on respondents' occupations, with a specific focus on the nickel processing industry, particularly for IWIP workers. The category of "Non-IWIP Workers" encompasses individuals who do not work for IWIP and are employed as fishermen, farmers, health centre workers, or who are unemployed.



Gambar 3.7. Perbandingan berdasarkan pekerjaan: Pekerja IWIP dan Bukan Pekerja IWIP.

Arsenic and Mercury

Blood levels of mercury and arsenic were higher in residents who were not IWIP workers. The average blood mercury level for IWIP workers was 8.8 µg/L, close to the safe limit of 9 µg/L, while non-IWIP workers had a 9.5 µg/L level.

The average blood arsenic level for IWIP workers was 10.4 µg/L, while for non-IWIP workers it was 14.7 µg/L. This information suggests that the main exposure to arsenic and mercury does not originate from occupational sources.

Methyl Mercury, the most toxic Mercury form, commonly found in Fish

Mercury is a highly hazardous heavy metal that poses a significant threat to human health. The Minamata Convention addresses the use, distribution, and reduction of mercury. This metal causes irreversible health damage by affecting the kidneys, liver, digestive system, heart, lungs, and nervous system. Mercury is classified as a neurotoxin, which is particularly toxic to the nervous system, especially the brain and fetal neural development. It can hinder fetal neural growth, potentially leading to birth defects and developmental disorders.

High mercury levels in the blood typically indicate exposure to organic mercury, which can occur through the consumption of fish containing methylmercury or through recent exposure to mercury vapor. For most individuals, elevated blood mercury levels are primarily linked to eating fish and seafood that contain organic mercury. However, having high mercury levels in the blood does not necessarily mean that a person will immediately experience negative health effects. Instead, these elevated levels serve as a warning sign of exposure, highlighting the need to take measures to reduce further exposure before any harmful effects can develop [76].

Arsenic Toxicity differs by Species

Arsenic exposure affects multiple organ systems, contributing to serious health conditions such as diabetes, hypertension, cardiovascular diseases, and fertility issues [77]. Long-term As exposure may increase the risks of diabetes, cardiovascular disease, nerve dysfunction, and prostate cancer (Cantor and Lubin, 2007; CoronadoGonzalez et al., 2007; Boamponsem et al., 2010). Coal-fired energy production and traffic emissions are generally considered the major sources of atmospheric As in urban areas (Pacyna and Pacyna, 2002) [78].

Human exposure primarily comes from groundwater, drinking water, seafood, and metal ore smelting/refining. Seafood—including fish, shellfish, and seaweed—is the largest contributor to arsenic exposure in human populations. Total arsenic concentrations in shellfish are typically higher than in fish. While arsenic in fish is typically organic and non-toxic, not all inorganic arsenic is converted. Therefore, the risks of arsenic exposure should still be considered. Certain seaweed and shellfish species can accumulate high concentrations of inorganic arsenic. According to the World Health Organization (WHO), inorganic arsenic has high acute toxicity. The International Agency for Research on Cancer (IARC) classifies inorganic arsenic as a Group 1 carcinogen, meaning it is carcinogenic to humans.

High concentrations of arsenic in the blood are detected soon after exposure, as arsenic swiftly enters body tissues. The body processes arsenic similarly to phosphate, incorporating it into areas where phosphate is typically found. Arsenic is generally not detectable in blood samples more than two days following exposure, making blood tests useful only for recent exposure. The half-life of inorganic arsenic in the blood ranges from 4 to 6 hours, while its methylated metabolites have a half-life of 20 to 30 hours. Therefore, blood arsenic levels that exceed the safe limit of 12 µg/L indicate significant exposure [79].

Both metals can enter the body from various environmental exposure routes, including food. This finding aligns with data on heavy metal levels in fish catches, indicating higher concentrations of arsenic and mercury.

The IWIP workers who were our respondents had a working time range of 48-72 hours per week with a shift/rotation system; the company provided lunch for workers with various menus, such as chicken, fish, and vegetables. There is no information about the fish supplier for the workers' food at IWIP, so it is assumed that the fish the company serves does not come from the waters of Weda Bay.

This assumption is supported by interviews with fishermen from several media outlets, who say that the company no longer buys fish from fishermen, as Weda Bay Nickel used to do before IWIP was established.

However, workers still consume fish purchased from traditional markets or Weda fishermen outside working hours. Based on data on fish caught in Weda Bay which are positively contained mercury and arsenic, the indication of environmental exposure to

mercury and arsenic through seafood for the non-IWIP worker community is potentially more significant than that of IWIP workers.



Figure 3.8. IWIP Workers after their work shift. (Photo: Hariyanto Teng)

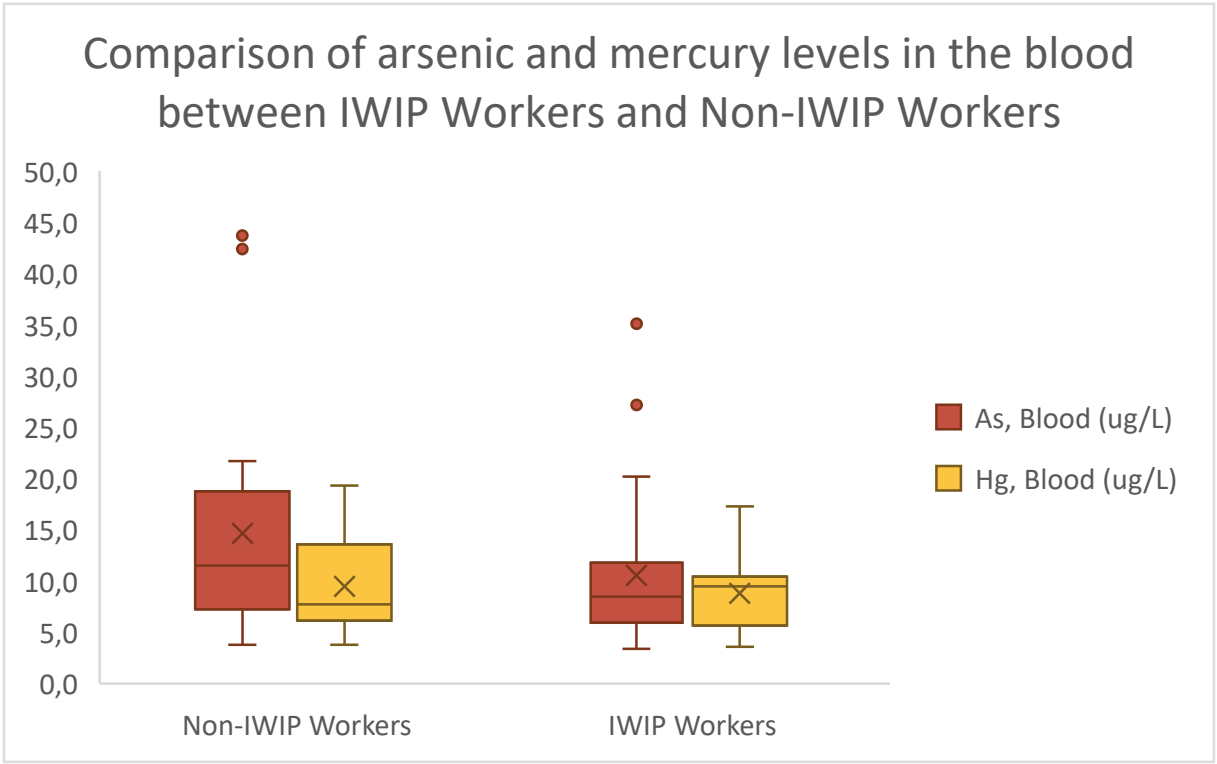


Figure 3.9. Comparison of Arsenic and Mercury levels in the blood between IWIP Workers and Non-IWIP Workers

Lead, Cadmium, and Nickel

Lead, cadmium, and nickel are more commonly associated with occupational exposure. IWIP workers have an average blood cadmium level 2x higher than non-IWIP workers. The average blood nickel level of IWIP workers is slightly higher than that of non-IWIP workers.

This may be influenced by nickel exposure through the dermal and inhalation routes due to the characteristics of the job that comes into contact with nickel materials. Meanwhile, the average blood lead level of non-IWIP workers is slightly higher than that of IWIP workers.

"There is no safe blood lead level"

Lead exposure is widely linked with occupational hazards, but it can also occur through lead emissions from coal combustion, gasoline, and waste incineration. Lead was historically used in household paint, which can deteriorate over time, releasing dust that children may inhale or ingest. Parents exposed to lead at workplaces generally bring lead dust to their home with clothes or on their skin, thus increasing the chances of exposure in their children (Watts, 2009) [80]. Lead poisoning refers to the health issues and symptoms that arise from exposure to lead, which can have lasting effects on children's physical and mental development. Other sources of lead exposure include leaded gasoline, household dust, ceramic porcelain, mining activities, lead-contaminated soil, lead pipes, lead-acid batteries, and more.

In the human body, lead exerts its toxicity through several mechanisms. It inhibits key enzymes in heme synthesis, such as aminolevulinic acid dehydratase (ALA-D) and ferrochelatase, leading to anemia. Lead binds to functional groups in the amino acid cysteine, which is essential for protein formation. Through another mechanism, lead absorbed by the body primarily accumulates in bones and red blood cells [81,82]. Most lead is stored in bones, with a half-life of 25–30 years (Agency for Toxic Substances and Disease Registry, 2007 and 2012).

Blood lead levels (BLL) between 25–60 µg/dL can cause neuropsychiatric effects such as difficulty concentrating, headaches, irritability, and more. Anemia typically occurs when BLLs exceed 50 µg/dL. The threshold BLL for individuals over seven years old is 9 µg/dL [80].

Unrecognized Cadmium Exposure

The primary source of airborne cadmium is smelting, followed by the combustion of fossil fuels such as coal and oil, as well as waste incineration. Due to its unfavorable combination of high toxicity and volatile nature, cadmium is classified as an airborne pollutant with significant environmental and human health risks [83]. Ambient air cadmium levels are generally low, except in areas near industries that emit cadmium [84].

Smoking is another major route of cadmium exposure, as tobacco plants efficiently absorb cadmium from the soil. On average, smokers have blood cadmium levels twice as high as non-smokers. Dietary cadmium exposure typically occurs through vegetables such as lettuce, spinach, and potatoes grown in high concentrations.

Global health organizations, including the International Agency for Research on Cancer (IARC) and the U.S. EPA, classify cadmium as a potential carcinogen. IARC recognizes cadmium as a known human carcinogen, while the U.S. EPA classifies it as a probable human carcinogen via inhalation.

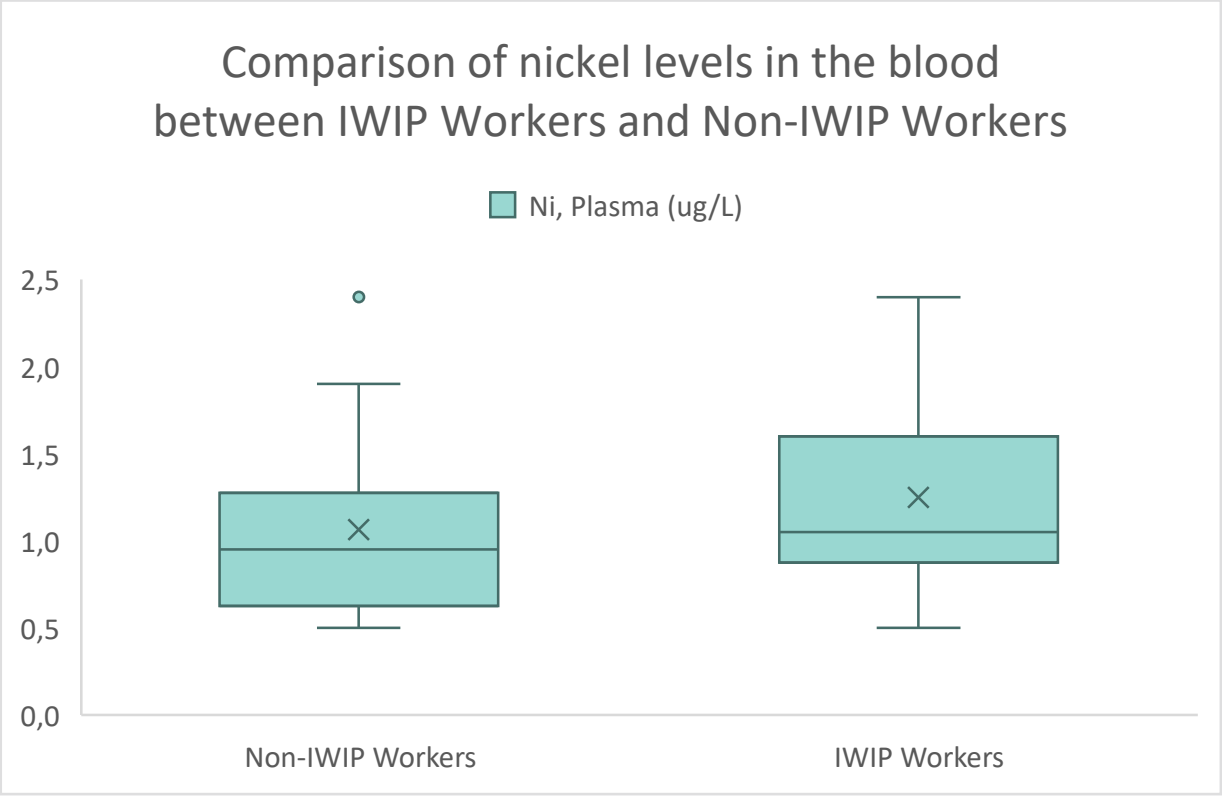


Figure 3.10. Comparison of Nickel levels in the blood between IWIP Workers and Non-IWIP Workers

The iron and steel industry has the potential to emit cadmium in several stages of its production. Although cadmium levels are low in most steelmaking input materials, the large volume of material used daily creates the potential for significant cadmium release into the environment[66].

Stainless steel production uses the same process as steel production in general, with the addition of other methods [85]. Iron ore, including laterite, contains cadmium in small concentrations. Since most processes in the iron and steel industry operate at temperatures above the boiling point of cadmium, cadmium evaporates and is emitted through the off-gas process as particulates [86].

Particulate capture technologies, including baghouses and scrubbers, are crucial for reducing cadmium emissions into the air [87]. The effectiveness of these technologies significantly impacts worker exposure to cadmium.

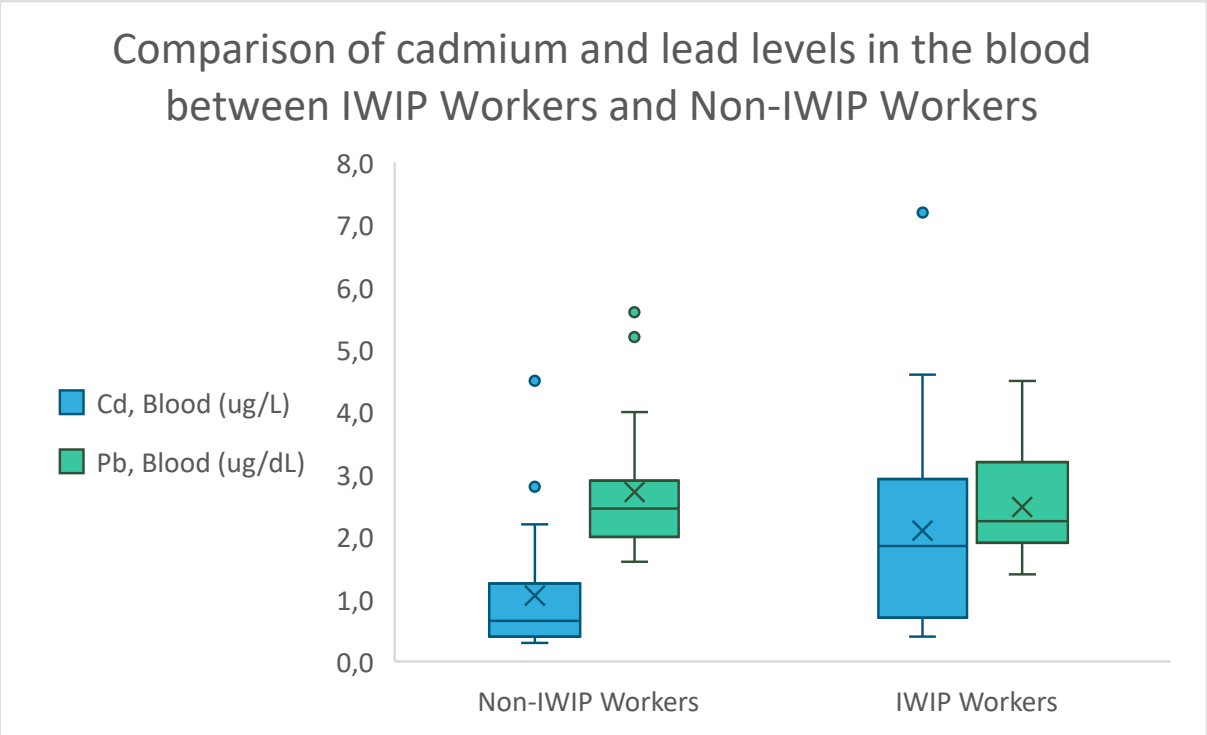


Figure 3.11. Comparison of cadmium and lead levels in the blood between IWIP workers and non-IWIP workers

Besides occupational exposure, cadmium exposure may also happen through smoking habits. Of the 46 respondents, 27 were smokers, while 19 were non-smokers. The cadmium levels in smokers were three times higher than those in non-smokers. Among the 26 respondents working at IWIP, 73% were smokers. Smoking has the potential to be a significant source of cadmium exposure in the blood of IWIP workers.

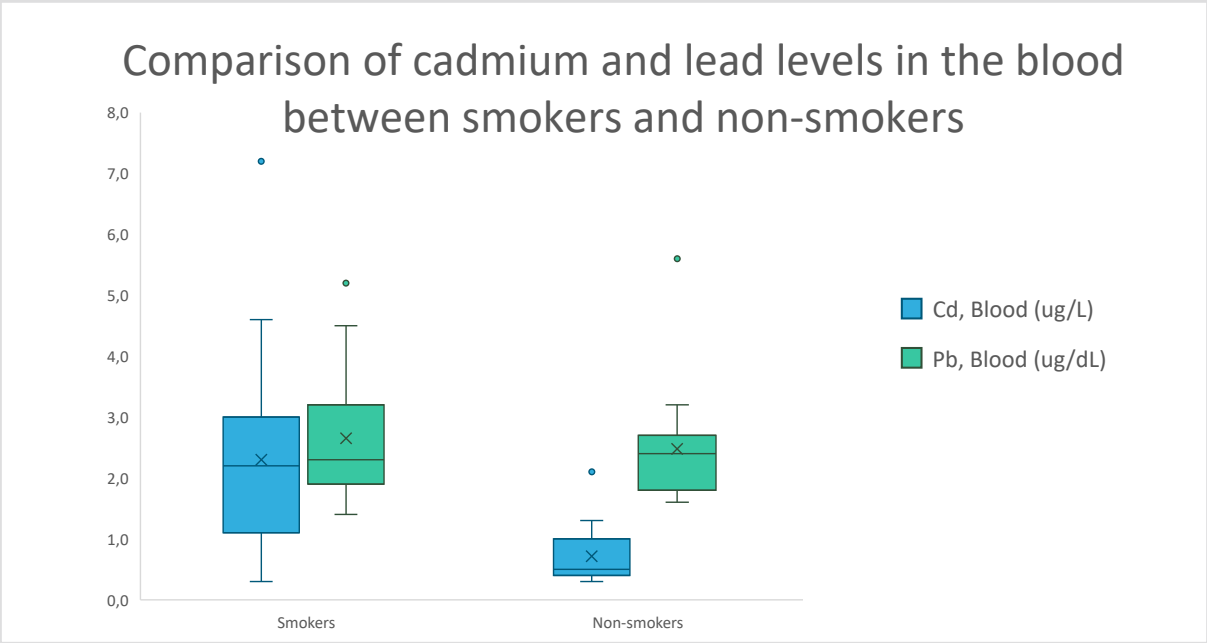


Figure 3.12. Comparison of cadmium and lead levels in the blood of IWIP workers and non-IWIP workers

3.3.2. Potential Route of Exposure: Direct and Indirect

Workers are exposed to various heavy metals daily. These materials, such as coal, nickel ore, and nickel products, can be directly or indirectly exposed. Jobs in the "Direct" exposure category include those who work in Rotary Kilns, Dump Truck Operators, Furnaces, Welders, Coal Storage, and others.

The "Indirect" exposure category includes individuals who primarily work indoors and do not come into direct contact with these materials, such as X-ray analysts, chefs, and construction workers. A comparison of the two categories of worker exposure to materials with the potential to cause heavy metal contamination did not reveal a significant difference in value. However, the distribution of cadmium concentration data among IWIP workers who have direct contact with these materials is slightly higher than that of those without direct contact.

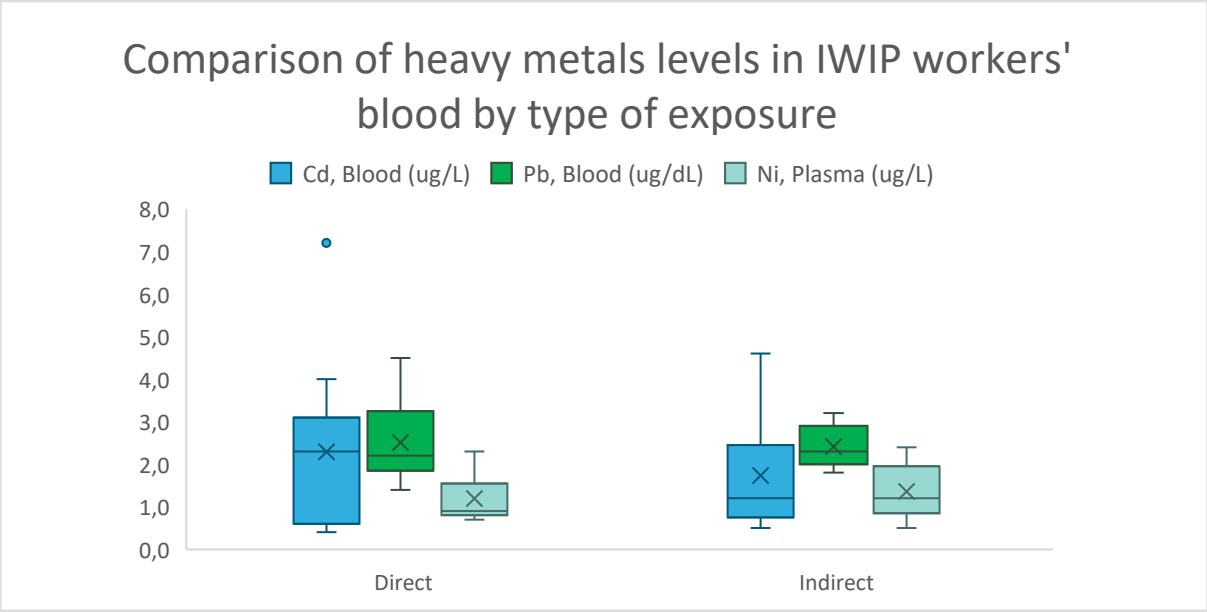


Figure 3.13. Comparison of heavy metal levels in the blood of IWIP workers by type of occupational exposure

Key Highlights: Human Biomonitoring in Weda Bay area 2025

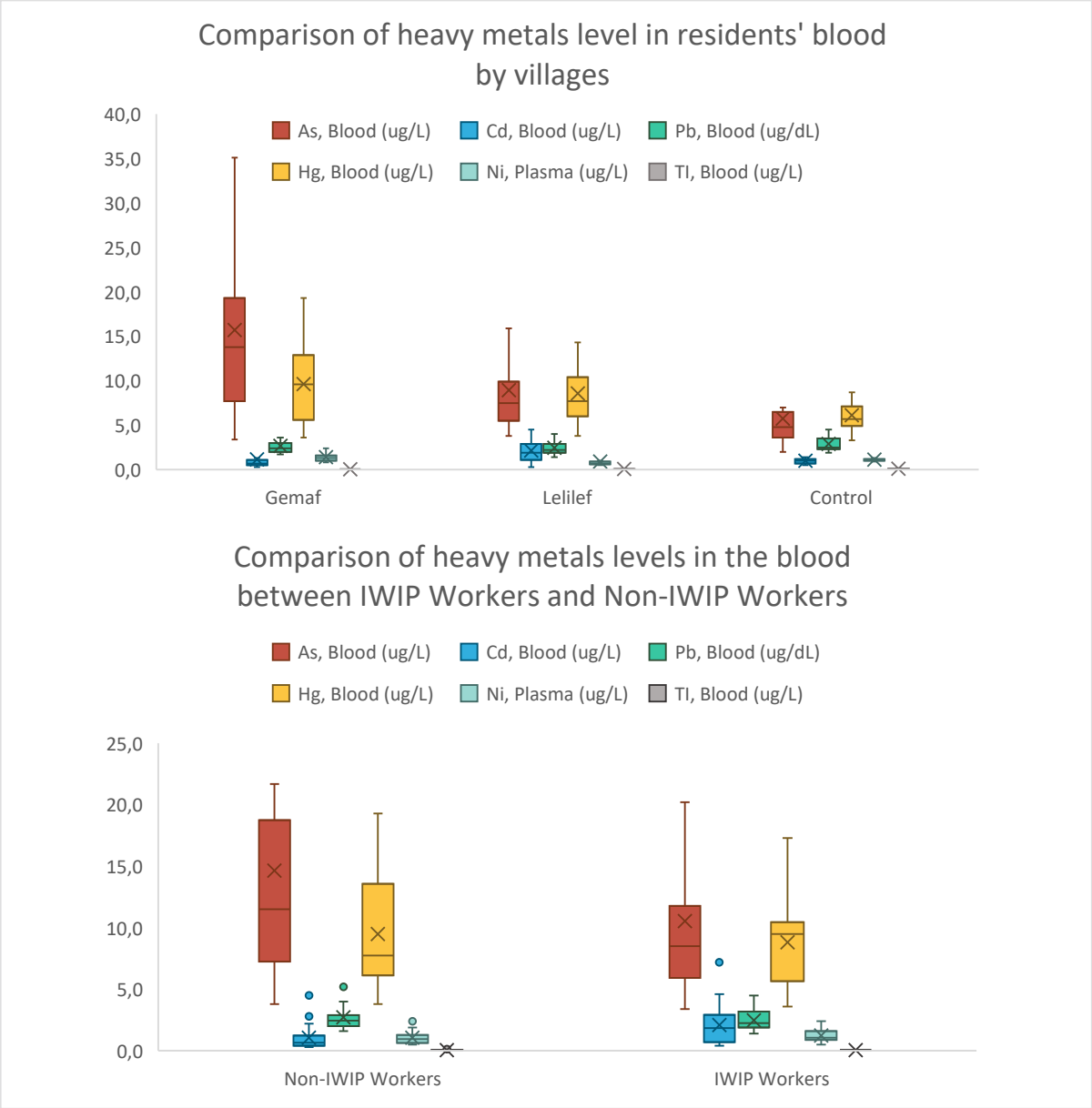


Figure 3.14. Heavy metals concentration in residents' blood in Weda Bay based on (a) villages and (b) occupation

The examination of heavy metal concentrations in the blood revealed that 22 individuals (47%) had mercury levels exceeding the safe limit of 9 µg/L. In comparison, 15 individuals (32%) had arsenic levels surpassing the safe limit of 12 µg/L out of 46 community respondents who participated. The concentrations of nickel, thallium, lead, and cadmium in the blood of 46 individuals were below the safe limit value. Overall, Both target communities showed higher levels of heavy metals concentrations in blood than that of the control.

Blood levels of mercury and arsenic were higher in residents who were not IWIP workers. The category of "Non-IWIP Workers" encompasses individuals who do not work for IWIP and are employed as fishermen, farmers, health centre workers, or who are unemployed. This information suggests that the main exposure to arsenic and mercury does not originate from occupational sources.







4 Overlooked Impacts on the Environment and Public Health

4.1. Potential "Cocktail Effects" on Human Health

Data on the toxicity characteristics of each heavy metal in the human body have been extensively gathered, and various recommendations for mitigating their effects are available. However, information regarding the combined effects of several heavy metals in the human body remains unknown. The cocktail effect, which refers to the toxic impact of a combination of multiple pollutants, is often overlooked despite its significant potential danger. For instance, some compounds at doses below the safe limit may not harm the body but could become toxic when they synergise with other pollutants [88]. One pertinent example is cancer.

Cancer formation is closely associated with reactive oxygen species (ROS) activity, which causes oxidative stress. Oxidative stress interacts with three stages of cancer formation. ROS inflict DNA damage through gene mutations, changes in DNA structure, abnormal gene expression, disruption of intercellular communication, and modification of secondary signalling systems. Of the six heavy metals, cadmium and arsenic are classified as carcinogenic. Arsenic and its metabolites can stimulate the production of ROS [89,90].

Increased ROS was detected in cadmium and contributes to cancer formation through several other chemical reactions in the body [91]. Research also shows that mercury can induce ROS formation, which causes cell DNA damage and initiates the carcinogenic process [92]. However, the general characteristics of individual metals already significantly contribute to cancer formation, mainly when these metals simultaneously affect the body.

The University of Gothenburg in Sweden found that the combined effects of several chemical compounds are more toxic than their individual effects. Based on this finding, EU environment ministers are urging the European Commission to change chemical risk assessments and amend existing legislation on the effects of chemical combinations[93].

4.2. Impacts on Biodiversity

According to the 2017 Species Richness and Relative Abundance of Reef-Building Corals in the Indo-West Pacific report, Halmahera has the highest concentration of coral diversity in the world [94]. Weda Bay boasts high marine biodiversity and a rich variety of coral habitats. It is situated outside the tropical storm zone, which allows coral to thrive without disruption. For example, Widi Island in the Weda Bay area has a substantial soft coral cover and high fish density[95]. Large coral colonies, often predicted to be hundreds to thousands of years old, are typically found in a robust condition.

Fishery resources, including fish, sea cucumbers, crabs, shrimp, and algae, are abundant. Various types of echinoderms, such as starfish (Asteroidea), sea urchins (Echinoidea), and sea cucumbers (Holothuroidea), which prefer clear and relatively calm waters, can be observed [96].

Hemiscyllium halmahera, commonly known as the bamboo or walking shark, is found in Weda Bay. This nocturnal shark, characterised by its spotted patterns, inhabits the benthic zone (the ocean floor) and was discovered by Allen, Erdmann, and Dudgeon in 2013 [97,98]. This Halmahera endemic animal lives in groups and is often found in environments with good mangrove, seagrass, and coral reef ecosystems. The International Union for Conservation of Nature (IUCN) data shows that the Halmahera walking shark is near threatened [99].

Weda Bay is in the heart of the Coral Triangle, the world's most important coral reef system. It represents 30% of the world's coral reefs despite only occupying 1.5% of the ocean. Using processed Landsat 7ETM imagery, Djamhur et al. found 85 types of coral clusters with a total area of 1773.41 hectares in Weda Bay[100].

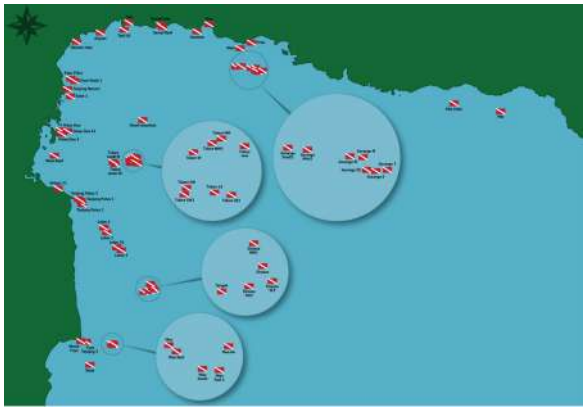


Figure 4.1 Dive locations at several points with coral reef biodiversity around Weda Bay (Photo: Weda Bay Resort)



Figure 4.2 Coral Reef Colony of Weda Bay. (Photo: Nicole Helgason, Canadian Coral Reef Scientist)



Figure 4.3 Close up of Montipora coral showing small purple polyps. (Photo: Vincent Chalias)

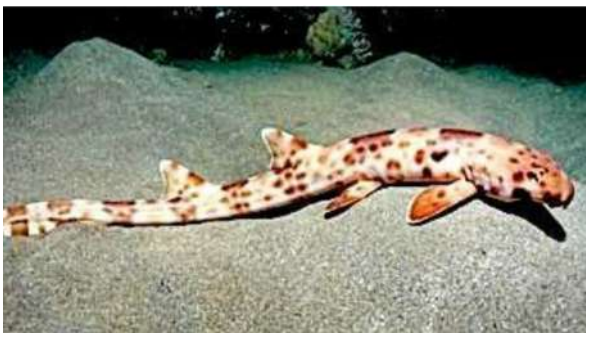


Figure 4.4 *Hemiscyllium halmahera* in the waters near Halmahera. (Photo: Mark Erdmann, California Academy of Sciences, https://commons.wikimedia.org/w/index.php?curid=30260864)

The results of the suitability analysis from a study conducted by Djamhur et al. in 2014 on the estimation of marine ecotourism utilisation in Weda Bay revealed the potential for diving ecotourism covering an area of 488.8427 hectares, snorkelling ecotourism covering 551.737 hectares, and mangrove ecotourism covering 620.1251 hectares [100]. These figures are competitive compared to similar analyses conducted by Yuanike et al. (2020) in Raja Ampat, one of Indonesia's most popular marine ecotourism destinations, shows the potential for diving ecotourism covering 463.1896 hectares, snorkelling ecotourism covering 159.24 hectares, and mangrove ecotourism covering 135.22 hectares[101].

The nickel industry in Halmahera poses significant threats to biodiversity, profoundly impacting the delicate ecosystems that characterise this rich region. Nickel mining leads to deforestation, habitat destruction, and soil erosion [102]; disrupting the habitats of numerous vulnerable endemic species due to limited ranges and environmental pressures. The loss of biodiversity threatens plants and animals and destabilises the broader ecosystem, impacting services such as pollination, water purification, and carbon sequestration, which are crucial for environmental health.

The expansion of industry concerns the traditional economy: ecotourism and coastal livelihoods. Halmahera has stunning natural landscapes and rich marine biodiversity, attracting tourists seeking unique experiences. However, as mining operations expand, scenic areas are compromised, diminishing their appeal and potentially leading to a decline in tourist numbers.



Weda Bay blew my mind! It was amazing what I saw in 2018, there were the biggest coral colonies and the biggest coral I've ever seen, right there, by the shore of Kobe Reef. There were corals I had never seen anywhere else. So many big corals, huge huge ones, with huge diversity of corals. I've seen a lot of corals in Indonesia, from North Sulawesi to Raja Ampat, but this one is special.

Nicole Helgason,

a Canadian Coral Specialist

4.3. Captive Power Plant Impacts to the Environment

4.3.1. Coal as Marine Pollutant

On the day of the environmental sampling, the team found the beach in Gemaf filled with coal and black seawater. The seawater contained black particulates or fragments, and the coal chunks varied from medium to small. The presence of coal in the aquatic environment can damage the marine ecosystem and potentially harm aquatic organisms.



Figure 4.5 Coal washed out to coastal areas affecting the beach and sea water quality (source: Nexus3 Foundation)

Coal is a fuel containing high carbon and is also typical of impurity compounds from the earth's interior. These compounds include heavy metals and several organic compounds, such as polycyclic aromatic hydrocarbons (PAHs) [103,104]. The composition of coal varies wildly, depending on the geological conditions and coal seams where it is mined. In addition, the purity level of coal also affects the composition of impurity compounds in coal [105].

Many heavy metals from coal mining and combustion are toxic to the environment and biodiversity. Mercury is naturally concentrated in sulfide ore, making it an impurity in fossil fuel deposits. Coal has a higher Hg content than other fossil fuels, with a concentration of 0.01 - 1 ppm in mass [106,107].

Coal is a source of heavy metal pollution because its compounds can leach into water bodies. The chemical composition of coal is essential to determining the type of compounds leaching into water bodies. Coal with a high sulfur content is more likely to produce leachate in acidic conditions that can cause acidification [108].

In coal combustion, heavy metals are generally bound together with combustion products, such as fly ash and bottom ash. However, mercury is also released as emissions into the atmosphere, which undergoes deposition into the soil or water (dry and wet deposition)

[92]. Coal-fired power plants are the second largest source of anthropogenic mercury emissions in the world, after small-scale gold mining (ASGM) [109].

Besides carbon emissions that threaten climate stability, heavy metals from coal combustion in fly ash and coal dust from coal combustion and coal storage can impact the respiratory system [110,111,112].

4.3.2. Coal Ash Pollution

Coal ash is a term that categorises waste or residue from coal combustion. Coal ash includes fly ash, bottom ash, boiler slag, and Flue Gas Desulfurization (FGD) process materials. These combustion products contain toxic compounds and are classified as hazardous waste. However, President Joko Widodo, through Government Regulation No. 22 of 2021, removed nine hazardous wastes, including fly ash and bottom ash (FABA), from the B3 waste (Hazardous waste) category to the registered non-B3 waste (Non-Hazardous Waste) category. As a result, the company's obligation to manage FABA is terminated, and it will generally be reused (repurposed).

Coal ash cases contaminating water bodies, including rivers, lakes, and groundwater, frequently occur in the United States and other countries. When coal ash is used as landfill material without additional layers underneath, such as geopolymer, heavy metals in the coal ash are released and leach into groundwater. In another instance, a coal ash reservoir leaked into the lake, poisoning fish with heavy metals, and the effects remain visible decades later.

To expand the IWIP airport, nickel smelter slags – another hazardous waste regulated under the new Government Regulation No. 22/2021 and FABA – are used as reclamation material over an area of 725,000 m²[113,114]. The landfilling or utilisation of hazardous waste is recognised as having the potential to generate a new source of pollution in the waters of Weda Bay.



Figure 4.6. Reclamation activities involving nickel slag are taking place near Cekel Airport. (source: Google earth satellite/SAS Planet)



Figure 4.7. A ship is depositing nickel slag onto the land. (source: Google earth satellite/SAS Planet)



Figure 4.8. Captive Power Plants in IWIP (Photo: Andri Saputra)

As a result of coal combustion, FABA indeed contains heavy metals in coal. The composition and concentration of heavy metals vary and adjust the source of the coal mined. However, FABA generally includes the most toxic metals in the world, such as arsenic, lead, mercury, cadmium, chromium, and selenium [115].

Arsenic was found in leachate fly ash from a coal-fired power plant in the Czech Republic, where arsenic transfer via waste was significantly higher than releases to air and/or water [116]. Research reveals that heavy metal concentrations are higher in fly ash and slag than coal. This phenomenon occurs due to the “enrichment” process, where heavy

metals from coal are concentrated in the final combustion products. The case of As and Hg metal enrichment in lignite coal occurs quite significantly in fly ash and slag; it is also found to be relatively high [117].

4.3.3. Thermal Pollution

Thermal pollution is defined as water quality issues arising from degradation processes that alter the ambient water temperature; it typically occurs due to the activities of coal-fired power plants [118]. These facilities require large quantities of water for their cooling systems, which, after use, are returned to the water body. Upon discharge, the average temperature can exceed normal levels, reaching above 27°C, coupled with high flow rates.

A sudden increase in water temperature causes organisms living in the water body to experience temperature shock, increased dissolved oxygen (DO), and the dissolution of toxic materials in the water [119]. This phenomenon disrupts the ecosystem because biota, especially organisms sensitive to temperature changes, find it challenging to adapt to sudden changes in environmental temperature. High temperatures can also damage aquatic ecosystems [120], coral, seaweed, and shrimp cultivation.

4.3.4. Radioactivity from coal-fired power plants

Coal combustion as a fuel for power plants leads to the redistribution of natural radionuclides originating from coal, which are concentrated in fly ash and bottom ash [121]. Coal naturally contains several radionuclides, such as Ra-2226, Th-232, K-40, U-235, U-238, and Pb-210 [122]. Coal, like most materials found in nature, contains trace quantities of the naturally occurring primordial radionuclides, i.e. of 40K and 238U, 232Th and their decay products. Therefore, the combustion of coal results in the release into the environment of some natural radioactivity (1.48TBqy−1), the major part of which (99%) escapes as very fine particles, while the rest in fly ash. Thus, fly ash and bottom ash also contain radionuclides[123].

All conversion forms originating from coal in the industrial process will produce products/materials/waste. Products containing natural radionuclides are called technologically enhanced naturally occurring radioactive materials (TENORM) [124,125]. TENORM is generally found at very low concentrations and is part of everyday human life. However, some TENORM have high radionuclide concentrations that can increase radiation exposure in the surrounding environment.

Indonesian coal has an average uranium content of 0.2 mg/kg and thorium of 0.67 mg/kg [126]. For coal consumption of 20.046 million tons and 22.995 million tons, then after calculating the average U content is 4 and 4.6 tons while the Th content is 13.4 and 15.4 tons [126].

Radionuclide enrichment (TENORM) that occurs after coal combustion into fly ash and bottom ash ranges from 5.2 to 9.7 times. After coal combustion, fly ash is produced with a TENORM enrichment factor ranging from 5 to 10 times [121,125,127].

In Indonesia, the highest enrichment for bottom ash is found in the radionuclide Pb-210, where in all coals, it has a concentration of 3.084 Bq/kg after combustion Pb-210 is measured to be 22.367 Bq/kg with an enrichment factor of 7.7 times. For fly ash, the highest enrichment is found in U-235 from a concentration of 0.057 Bq/kg to 0.553 Bq/kg with an enrichment factor of 9.7 times[126].



5 Conclusions and Recommendations

5.1. Conclusions

The expansion of nickel industrial mines and processes in the Weda Bay area,North Maluku significantly affects local people's environment, public health, and social well-being. Water source contamination, biodiversity loss, and deforestation threaten the overall balance of ecological health and community livelihood.

Environmental Impact

The water quality of Ake Jira has deteriorated from Class I to Class III, raising concerns among the Weda communities who relied on it for drinking. Baseline data from 2007 supports these worries. Recent tests showed consistent heavy metal levels, with chromium and nickel exceeding USEPA standards, classifying the sediments of Ake Jira and Ake Sagea Rivers as "Heavily Polluted." According to Canadian guidelines, these chromium levels may threaten aquatic life, while other heavy metals were within safe limits.

Additionally, fish from Weda Bay have been found to contain arsenic and mercury. Arsenic levels have drastically increased, now 20 times higher than in 2007, posing health risks, while mercury levels remain stable. We recommend testing for heavy metals at river mouths due to reported sediment buildup.

Human Biomonitoring

Our findings revealed that 22 individuals (47%) had mercury levels above the safe limit of 9 µg/L, and 15 individuals (32%) had arsenic levels exceeding the 12 µg/L limit. These results were based on blood samples from 46 community respondents, with higher levels found in residents who were not IWIP workers.

Surveys indicate that the primary exposure route is the consumption of fish caught in Weda Bay, as residents typically eat seafood two to three times per day. Fish sampling confirmed mercury and arsenic in all tested samples. Other metals, including nickel, thallium, lead, and cadmium, were below safe limits. Ongoing monitoring is crucial due to mercury and arsenic's potential long-term health effects.

Further research and monitoring are necessary to address the potential heavy metal contamination in Weda Bay. The Indonesian government should implement measures to reduce exposure, anticipating a rise in non-communicable diseases. Additionally, risks of food contamination and impacts on biodiversity and marine pollution need to be considered.

5.2. Recommendations

5.2.1. Environmental Aspects for Government and Regulators

- **Strengthen Environmental Monitoring**
    - The Ministry of Environment (MoE) or Environmental Agencies conduct regular independent monitoring of heavy metals in river water and sediment quality, separately from the company's mandatory environmental assessments, and expand the monitoring scope to include the estuary.
    - MoE installs ONLIMO (Water Quality Monitoring System) in rivers near mining sites, establishes clear parameters for heavy metal discharges from mining industries, and enforces compliance.
    - MoE should make environmental compliance data from industries in the area publicly accessible to ensure accountability and transparency.
    - The Ministry of Marine Affairs and Fisheries (MMAF) and MoE regularly monitor seawater quality in Weda Bay, particularly in areas prone to coal spills and waste discharge.
    - MMAF and National Research and Innovation Agency (BRIN) conduct periodic testing for heavy metals in fish and marine biota in Weda Bay and other regions with similar industries to anticipate and mitigate food contamination risks for local communities.
    - MMAF and The Ministry of Tourism and Creative Economy conduct a comprehensive investigation of the marine ecosystem in Weda Bay, including coral reefs, seagrass beds, and other critical habitats.

- **Strengthen Law enforcement**
    - MoE, in coordination with local environmental agencies, enhances regulatory oversight and enforcement mechanisms to ensure nickel mining and processing industries comply with waste management and emissions standards.
    - Law enforcement agencies impose stricter penalties for violations, conduct unannounced inspections, and require industries to comply with the regulations.

- **Review and strengthen industrial permit**
    - Reevaluate existing permits for nickel-related industries to ensure compliance with environmental standards, considering emission limits, waste management, and ecological impact. Introduce stricter permit conditions for new and existing operations to minimize environmental harm.
    - Assess the environmental carrying capacity of Weda Bay to quantify pollution levels and evaluate the area's ability to sustain industrial activities without exceeding ecological thresholds. This data will serve as a scientific basis for regulating further industrial expansion and rejecting proposals that risk exacerbating environmental degradation.

5.2.2. Health Aspects for Government and Regulators

- **Enhance Public Health Surveillance**
    - Local health agencies (Dinas Kesehatan) and Healthcare Facilities (Puskesmas) conduct routine health screenings, including heavy metal testing in blood, to assess exposure risks and provide early medical intervention for affected residents.
    - The Ministry of Health and Local health agencies conduct comprehensive surveys and studies on the prevalence of health issues in the area to identify trends, guide public health policies, and measure the long-term impact of industrial activities.
    - The Ministry of Health conducts a long-term projection of noncommunicable disease (NCD) prevalence over 5, 10, and 20 years to estimate potential economic losses from healthcare costs and reduced productivity due to heavy metal exposure.
- **Increase capacity of healthcare facilities and workers**
    - Strengthen healthcare facilities in the area to effectively manage the long-term impacts of heavy metal exposure by improving medical infrastructure, diagnostic capabilities, and treatment options.
    - Enhance the capacity of doctors and healthcare workers through specialized training on heavy metal poisoning, including its short-term and long-term health effects, early detection, and appropriate medical interventions.
- **Develop health awareness and education programs on heavy metals**
    - Develop a community education program on the risks of consuming heavy metal-contaminated seafood, especially predatory species with potentially high mercury levels.
    - Prioritize outreach to vulnerable groups, such as children and pregnant women, to minimize exposure and promote safer dietary choices through targeted awareness campaigns and nutritional guidance.

5.2.3. Nickel Mining and Processing Industry

- Enhancing occupational health and safety requires providing PPE, regular health screenings, and biomonitoring for workers handling hazardous materials.
- Transparent reporting mechanisms ensure accountability for workplace accidents and exposure incidents. Regular safety training on hazardous material handling and emergency response further strengthens workplace safety standards.
- Ensure responsible sourcing and processing by adopting advanced waste management, environmentally friendly extraction methods like improved HPAL, and robust supply chain traceability to uphold ethical and environmental standards.
- Ensure accountability and transparency in environmental data by regularly monitoring and publicly reporting emissions, waste management, and resource usage to uphold environmental standards and drive responsible industry practices.

5.2.4. Civil Society

- Raise Public Awareness by educating communities on environmental pollution and public health risks.
- Support Citizen Science and empower local communities to participate in data collection and environmental monitoring.
- Advocate for transparency and push for public access to environmental data to ensure government and industry accountability through evidence-based advocacy.

5.2.5. Researchers

- Advance independent monitoring by conducting and supporting research on biodiversity, health, and environmental impacts in Weda Bay and similar industrial areas.
- Initiate research on pollutant dynamics and environmental toxicology, such as metal bioavailability in the water, sediments, or benthic organisms to better understand industrial activities' potential long-term ecological impacts on marine life.
- Expand research on heavy metal pollution by collaborating with the government to study industrial contamination and its impact on surrounding communities.
- Conduct epidemiological studies to analyze noncommunicable disease prevalence in populations near pollution hotspots and guide public health strategies.

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Nexus3 Foundation

Nexus Foundation for Environmental, Health, and Development or Nexus3 Foundation works to protect the public, especially vulnerable populations, from the impacts of development on public health and the environment. Nexus3 works towards a just, toxic-free, and sustainable future.

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