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Research Article

Heavy metal contamination suspected of causing mass mortality in seaweed cultivation in waters affected by mining waste

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ABSTRACT

There has been a decrease and a mass death of seaweed, especially in centers where mining exploitation is located. This study was conducted to analyze the content of hazardous heavy at seaweed cultivation locations around the mining area of Morowali Regency. The data collection technique in this study is observation—water measurement and sampling at nine stations. The collected data were then analyzed by the International Modification Association of Official Analytical Chemists (AOAC) method 2005: 999.10, using Flame Atomic Absorption Spectrophotometer (FAAS) and Graphite Furnace Atomic Absorption Spectroscopy (GFAAS). The results showed that the heavy metal content in South Bungku Waters indicates that the heavy metal content is below the threshold the quality standard value based on PPRI no. 22 in 2021. Heavy metal content in Witaponda Waters and Bahodopi Waters indicates that the heavy metal content is above the threshold the quality standard value based on PPRI no. 22 in 2021. In Moahino Village was mercury (0.0036 mg/L) and lead (0.012 mg/L), in Ungkea Village was mercury (0.0018 mg/L) and lead (0.008 mg/L), in Emea Village was mercury (0.0079 mg/L), copper (0.009 mg/L), and lead (0.012 mg/L), in Bahodopi Village 1 was mercury (0.0024 mg/L), chromium (0.01 mg/L), copper (0.011 mg/L), and lead (0.013 mg/L), in Bahodopi Village 2 was mercury (0.0029 mg/L), chromium (0.02 mg/L), cadmium (0.002 mg/L), copper (0.012 mg/L), and lead (0.009 mg/L). It can be concluded that higher levels of heavy metals, which are more dangerous, can harm seaweed's cell structure. Seaweed productivity declines accordingly.

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INTRODUCTION

Several provinces in Indonesia as seaweed producers are South Sulawesi, Central Sulawesi, East Nusa Tenggara, West Nusa Tenggara, East Java, Maluku, and Bali. From 2014 to 2016, Central Sulawesi Province was ranked second as Indonesia's largest seaweed producer, after South Sulawesi Province. This is supported by the availability of resources, namely extensive cultivated land considering the length of the coastline of 4,013 Km as a potential seaweed development area owned by Central Sulawesi Province [1]. The availability of seaweed cultivation land differs from its utilization, which has only reached 7%, thus causing the need for utilization efforts to increase Central Sulawesi seaweed production [2]. In the process of seaweed development in Central Sulawesi, seaweed has been determined as a strategic leading aquaculture commodity in Central Sulawesi Province due to its advantages over other commodities, such as massive production. Seaweed and macroalgae are frequently thought of as extra biomasses that could aid in the development of novel feed and food items, helping to allay grave worries about the future food security of humanity [3]. With more and more macroalgae being tested for a variety of uses, including as novel foods, seaweed and macroalgae may become more and more important in tackling these issues. Since it does not compete with other uses of freshwater resources or arable land, the production of macroalgal biomass is attractive from an economic and sustainable standpoint [4].

On the other hand, mining expansion in Morowali Regency, Central Sulawesi, went unchecked. In the last dozen years, forest areas that should have been protected have been destroyed. Mangrove forests stretching on Tambayoli Beach, Tamainusi, and Tandoyondo are now cut down by trees [5]. The land will be used as a nickel-loading port. On the environmental side, the coal mining business is considered the most destructive compared to other natural resource exploitation activities because it changes the shape of natural fortifications, damages or disappears vegetation, produces tailings waste and waste rock, and drains water, soil, and surface water. If not rehabilitated, former mining lands will form giant puddles and arid expanses of acidic land. Heavy metals are metallic elements with a density of > 5 g/cm3 in seawater. Heavy metals occur in dissolved and suspended form [6]. Under these natural conditions, organisms require heavy metals to grow and develop. Increased levels of heavy metals in water will result in heavy metals initially needed for various metabolic processes turning into toxins for aquatic organisms [7]. Besides being toxic, heavy metals accumulate in sediments and biota through bioconcentration, bioaccumulation, and biomagnification by marine life [8]. Heavy metals that enter the body of animals are generally no longer excreted from their bodies. Because of this, these metals tend to accumulate in their bodies. As a result, these metals will continue to exist along the food chain. This is because predators at one trophic level eat their prey from the lower trophic levels that have been contaminated [9]. Thus, when toxic metals are added to the aquatic environments in which seaweeds are farmed or naturally occur, they readily accumulate in the multicellular marine macroalgae. As a result, the metals build up in the food chain, starting with absorption at the level of the primary producer and eventually reaching the consumer, where they enter the body. Although seaweed is a highly nutritious food, there is a great deal of worry about the possible negative health effects of consuming it, particularly when it comes to exposure to heavy metals and other chemical toxicants [10]. The persistent bioaccumulation of heavy metals in natural food chains has detrimental effects on human health as well as the ecosystem as a whole, particularly for direct and prolonged exposure [11]. Based on Musiige et al. [12] the possibility for high contamination levels of toxic metals such as arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), chromium (Cr), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) has the potential to pose risks to human life.

In addition, exploiting nickel ore in Morowali Regency is also a source of conflict, criminalization of the community, and environmental damage [13]. Water from the mine site flows into rivers and empties into the sea, potentially contributing heavy metals that will then accumulate in sediments: waters and seaweed itself. The nickel industry and mining are spread across various islands, such as Sulawesi, Maluku Islands, and Papua. This condition is not without impact; farming communities lose production space due to land use changes, both by legal procedures and land grabbing. When someone refuses to sell their land, farmers experience intimidation, forcing them to release their land, as happened in the Morowali District [14].

Morowali Regency is located in Central Sulawesi Province, the regency's capital. Its administrative center is in Bungku City. The administrative area of Morowali Regency consists of nine sub-districts, namely Bungku Tengah District, Bungku Barat District, Bungku Timur District, Witaponda District, Bungku Pesisir District, South Bungku District, and Bahodopi District [15]. Morowali Regency has been designated as one of the mining industry areas directed at the natural resource-based manufacturing sector because it has a large enough nickel source that it has the prospect of becoming the center of nickel-based industrial growth. The description above shows a significant decrease in seaweed production in Central Sulawesi Province, especially in the Morowali District. From 2012 until this year, there has been a decrease in the mass death of seaweed, especially in mining exploitation centers. This condition is very concerning, considering that mining products and seaweed commodities are regional assets that must go hand in hand, which can ultimately improve the economy of the community as a whole. Seaweed production in Morowali Regency from 2011 to 2021 is shown in Figure 1 below.

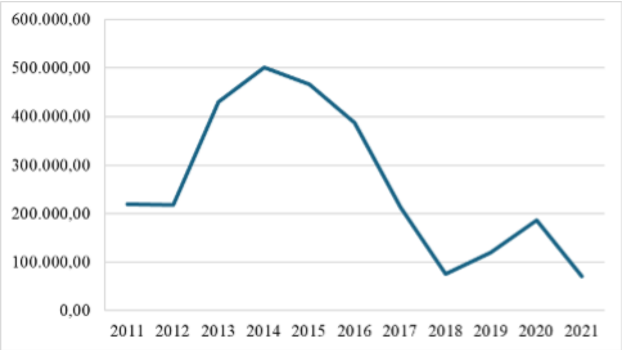

Figure 1. Seaweed production in Morowali Regency 2011-2021

Figure 1 shows the seaweed production in Morowali Regency from 2011 to 2021. During this period, the results fluctuated; from 2012 to 2014, there was an increase in the amount of production. Then, in 2014, there was a decrease until 2018. In 2018, there was an increase again until 2020, and in 2021, there was a decrease again.

Based on this background, this study was conducted to analyze the content of hazardous heavy metals such as Mercury (Hg), Chromium (Cr), Arsenic (As), Cadmium (Cd), Copper (Cu), Lead (Pb), Tin (Sn), and Nickel (Ni) at seaweed cultivation locations around the mining area of Morowali Regency. The hypothesis in this study is that the leading cause of the extinction of seaweed cultivated around the mining area is mining because it contains hazardous heavy metals in the form of Mercury (Hg), Chromium (Cr), Arsenic (As), Cadmium (Cd), Copper (Cu), Lead (Pb), Tin (Sn), and Nickel (Ni).

METHODOLOGY

Research Methods

This research uses experimental research methods, a scientific method conducted to test the cause-and-effect hypothesis between the independent variable (factors that are changed or manipulated in an experiment) and the dependent variable (results or responses measured in an experiment). This method is designed to systematically study the changes caused by the influence of the independent variable on the dependent variable. The data collection technique in this study is observation.

Research Location

Figure 2 depicts a map of sampling locations, showing where samples were collected for this research. Morowali Regency is between 2.6987° South Latitude and 121.9018° East longitude. The Morowali Regency region is shaped by 5.472 km2 of land. Morowali waters are located within the coral biodiversity triangle, home to many endangered corals. Coral reefs are habitats for a variety of economically valuable marine resources. Morowali Regency is one of four districts on Sulawesi Island with large nickel reserves. The nickel mining industry in Morowali Regency is progressing very rapidly. The widest potential for mineral and rock resources in the form of nickel potential is in the Districts of West Bungku, Central Bungku, East Bungku, Bungku Pesisir, and Bahodopi [16]. Each point in Figure 2 represents a specific location that can represent research results from the studied area.

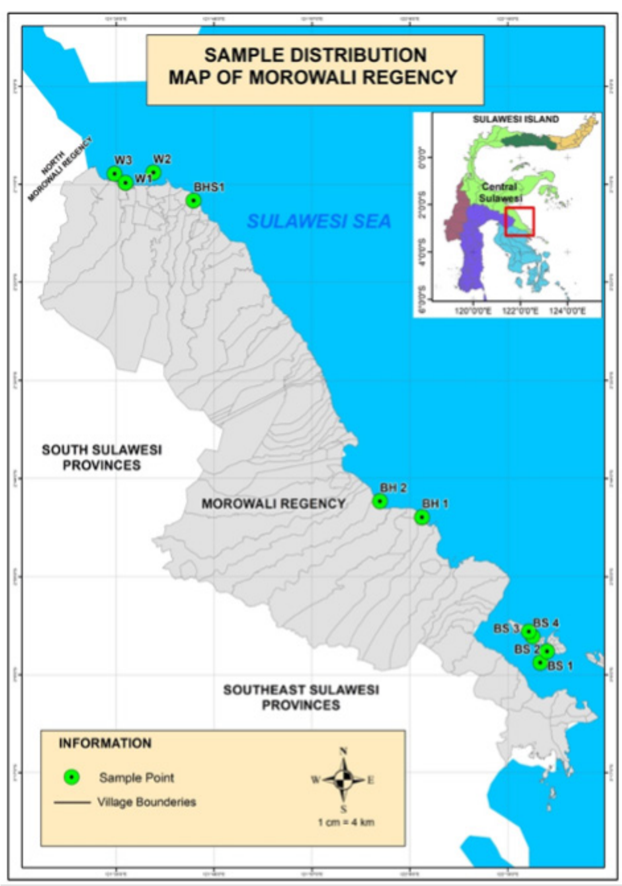

Figure 2. Water sampling location

As shown in Figure 3, the research location consists of four stations: a). Station 1 South Bungku Waters; b). Station 2 Bahodopi Waters; and c). Station 3 Moahino Waters. Table 1 shows several water and seaweed sampling locations that will be further analyzed for their heavy metal content.

Based on Table 1, it can be seen that there are ten sampling stations. Codes W1, W2, and W3 are in the waters of Wita Ronda Waters (Figure 3c). Codes BH1 and BH1 are in Bahodopi Waters (Figure 3b). Codes BS1, BS2, BS3, and BS4 are in the waters of South Bungku Waters (Figure 3a).

Research Procedures

The study was prepared by providing bottles and washing the bottles that would be used for sampling. Sample bottles were provided at the Laboratory of Productivity and Aquatic Environment (ProLink), Faculty of Fisheries and Marine Sciences IPB University, Bogor. Then, the bottles were washed using distilled water and 6% HCL to avoid sample contamination due to residue from plastic materials. Water samples were taken on a surface of as much as 250 ml at each station, and three repetitions were made based on SNI standards. The surface water samples involved inserting a sample bottle into the water's surface with the bottle's mouth facing the current so the water could directly fill the bottle. After filling the bottle, seal it and lift it to the surface. The water sample was previously treated with an 10% HCl solution to sterilize the bottles, labeled, and stored in a cool box. Water sampling was conducted at nine stations. Each station consists of 3 repetitions on the water's surface, in the middle, and near the bottom. Water samples were taken from the surface (0-1 m), middle (2-7 m), and bottom of the waters (8-10 m), carried out twice, and the second sample was taken three months after the first sample.

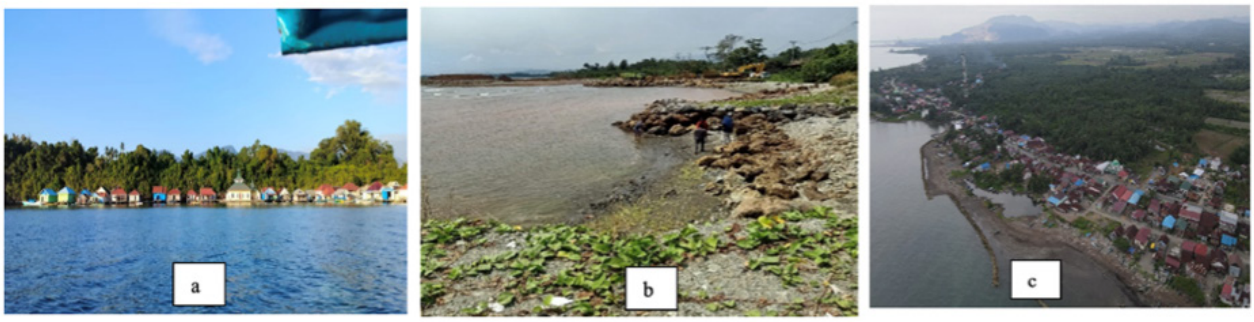

Figure 3. a) South Bungku Waters, b) Bahodopi Waters, and c) Wita Ponda Waters

Table 1. Location ordinate water and seaweed sampling

Station	Location	Latitude	Longitude
W1	Moahino, Wita Ponda	2.1930° S	121.5998° E
W2	Umbele, Bumi Raya	2.2001° S	121.6568° E
W3	Ungkaya, Wita Ponda	2.3091° S	121.5256° E
BH1	Fatufia, Bahodapi	2.9016° S	122.1121° E
BH2	Lalampu, Bahodapi	2.8951° S	121.9132° E
BS1	Kaleroang, South Bungku	3.0564° S	122.3858° E
BS2	Kaleroang, South Bungku	3.0564° S	122.3858° E
BS3	Pado-pado, South Bungku	3.0117° S	122.3476° E
BS4	Padabale, South Bungku	3.0296° S	122.3547° E

Table 2. Heavy metal analysis methods in water

No.	Heavy Metals in Water	Analysis Method
1	Mercury (Hg)+	IK-LAB-Metal-04 (Cold Vapor)
2	Chromium (Cr)+	IK-LAB-Metal-11 (Extraction-GFAAS)
3	Arsenic (As)+	IK-LAB-Metal-05 (Hydride)
4	Cadmium (Cd)+	IK-LAB-Metal-11 (Extraction-GFAAS)
5	Copper (Cu)+	IK-LAB-Metal-11 (Extraction-GFAAS)
6	Lead (Pb)+	IK-LAB-Metal-11 (Extraction-GFAAS)
7	Tin (Sn)+	IK-LAB-Metal-11 (Extraction-GFAAS)
8	Nickel (Ni)+	IK-LAB-Metal-11 (Extraction-GFAAS)

Measurement of Heavy Metals in Waters

The analysis of heavy metal content in seaweed was carried out by the Association of Official Analytical Chemists (AOAC) method international modification 2005: 999.10, utilizing Flame Atomic Absorption Spectrophotometry (FAAS) and Graphite Furnace Atomic Absorption Spectroscopy (GFAAS) (Table 2). A total of 0.5 grams of test seaweed and CRM were weighed, added with HNO3, and further digested using microwave digestion. The digested solution was then measured for total metal concentrations of copper (Cu), zinc (Zn), iron (Fe), cadmium (Cd), and lead (Pb) using FAAS and GFAAS. Parameters in the study of this method include linearity, detection limits, accuracy, and precision.

Data analysis carried out includes analysis of heavy metals Mercury (Hg), Chromium (Cr), Arsenic (As), Cadmium (Cd), Copper (Cu), Lead (Pb), Tin (Sn), and Nickel (Ni) in marine biota compared to the threshold values issued based on Government Regulation of the Republic of Indonesia

(PPRI) No. 22 of 2021 (Appendix VIII-Sea Water Quality Standards for Marine Biota) (Table. 3).

Table 3. Sea water quality standards PPRI No. 22 2021 for marine biota

Heavy Metals	Quality Standards (mg/L)
Mercury $(Hg)^+$	0.001
Chromium $(Cr)^+$	0.005
Arsenic $(As)^+$	0.012
Cadmium $(Cd)^+$	0.001
Copper $(Cu)^+$	0.008
Lead $(Pb)^+$	0.008
Nickel $(Ni)^+$	0.05

RESULTS AND DISCUSSIONS

Mining is an effort to develop mineral and energy natural resources that have the potential to be utilized sparingly and optimally for the benefit and prosperity of the people through a series of exploration, exploitation, and utilization of mining products [17]. These efforts rely on utilizing various resources, especially energy and mineral resources, supported by quality human energy resources, mastery of science and technology, and management capabilities. This may be because the location is close to the nickel sand spill. The industrial revolution and human activity have made environmental degradation worse. Large-scale pollution releases into the ocean have put coastal ecosystems at serious risk. Heavy metals (HMs) are extremely dangerous environmental contaminants due to their chronic toxicity, non-biodegradability, and environmental bioaccumulation. Heavy metals pose a major risk to human health and can be biomagnified and transported through food chains [18]. Most organisms' lives are significantly impacted by the bioaccumulation patterns of heavy metals (HMs), including chromium (Cr), cobalt (Co), copper (Cu), arsenic (As), nickel (Ni), mercury (Hg), and cadmium (Cd). Marine biota are negatively impacted by heavy metals from many distribution sources [19].

Cadmium (Cd), zinc (Zn), mercury (Hg), arsenic (As), silver (Ag), chromium (Cr), copper (Cu), iron (Fe), and platinum (Pt) are examples of heavy metals, which are elements with a higher atomic mass and density that can have an impact on both people and the environment. One of the biggest environmental issues affecting people, animals, and plants is heavy metal poisoning of water. Due to their inability to biodegrade, heavy metals can be dangerous even at low doses. There are three categories for metals and metalloid ions. Metals that are harmful at low concentrations, such as lead, cadmium, and mercury are included in the first group. The second group of metals—bismuth, indium, arsenic, thallium, and antimoney—are less harmful, while the third group consists of necessary metals like zinc, cobalt, copper, iron, and selenium that are only harmful at high concentrations and are involved in a number of chemical or biochemical processes in the body [20].

Mercury belongs to pollutants that are harmful to human health, so its presence in the environment must be considered. All forms of mercury, both in methyl form and alkyl form that enter the human body continuously will cause permanent damage to the brain, liver, and kidneys [21]. Waters polluted with mercury-heavy metals not only endanger the biota communities that live in these waters but will also endanger human health [22]. This is due to the nature of heavy metals that are persistent in the environment, are toxic at high concentrations, and tend to accumulate in biota. Methyl mercury compounds that enter the food chain accumulate in fish and biota in the sea [23]. Nickel is one of the most critical metals and has many industrial applications. There are many types of nickel products, such as fine metals, powders, sponges, and others. Due to its corrosion-resistant and high-temperature-resistant properties, 62% of nickel metal is used in stainless steel, and 13% is consumed as superalloys and non-ferrous alloys [21]. Depending on age and duration of exposure, inorganic arsenic (As) exposure in mammals can induce lung malignancies, damage to the neurological system, and occasionally even death. A rising amount of studies links exposure to cadmium (Cd) to taste impairment, osteoporosis, renal failure, and malignancies in important organs. Early childhood development delays are also linked to lead (Pb) exposure [24].

Existing Conditions of Heavy Metals in South Bungku Waters

The levels of heavy metals in exposed seaweed tissues depend on several factors, including species-specific absorption capacity, water temperature, pH, salinity, and the quantities of the pollutants in the surrounding environment. Many areas lack the understanding of heavy metal concentrations in kelps, both farmed and wild, necessary to establish suitable regulatory recommendations, despite the growing demand for seaweed-specific consumer guidance and serving sizes. Figure 4 below shows the heavy metal content in South Bungku Waters (mg/L).

Figure 4 shows heavy metals in South Bungku Waters. Hg and As have different organic and ionic speciation. In this study, the total content of Hg and As has been measured and presented in graphical form (Figure 4, 5, and 6). Based on Table 4 there are four villages that were used as sampling locations in South Bungku Waters, namely Kaleroang Village 1, Kaleroang Village 2, Padabale Village, and Pado-Pado Village.

The results based on Table 4 showed that the heavy metal content in Kaleroang Village 1, Kaleroang Village 2, Padabale Village, and Pado-Pado Village indicates that the heavy metal content is below the threshold the quality standard value based on PPRI no. 22 in 2021.

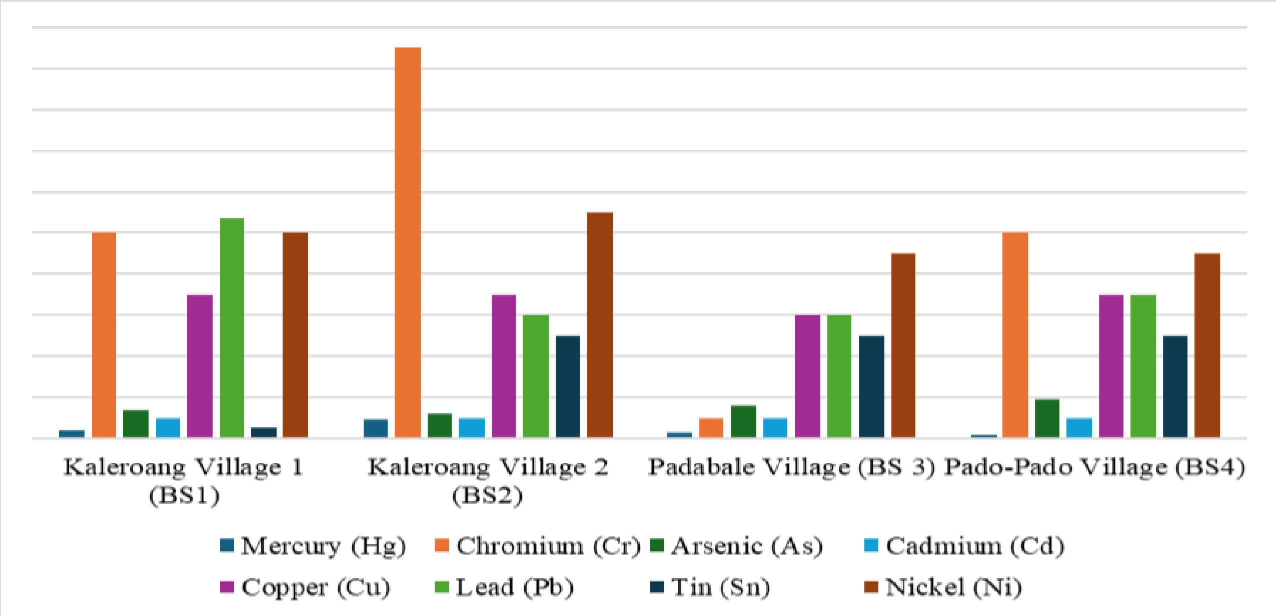

Figure 4. Profile of heavy metals in South Bungku Waters

Table 4. Heavy metals content in South Bungku Waters (mg/L)

Village	Mercury (Hg)	Chromium (Cr)	Arsenic (As)	Cadmium (Cd)	Copper (Cu)	Lead (Pb)	Tin (Sn)	Nickel (Ni)
Kaleroang Village 1 (BS1)	0.0004	< 0.010	0.0014	< 0.001	0.007	0.007	<0.0005	0.010
Kaleroang Village 2 (BS2)	0.0009	<0.019	0.0012	<0.001	0.007	<0.006	<0.005	0.011
Padabale Village (BS 3)	0.0003	<0.010	0.0016	<0.001	0.006	0.006	<0.005	0.009
Pado-Pado Village (BS4)	0.0002	<0.010	0.0019	<0.001	0.007	0.007	<0.005	0.009

Figure 5 shows heavy metals in Witaponda Waters. Based on Table 5 there are three villages that were used as sampling locations in Witaponda Waters, namely Moahino Village, Ungkea Village, and Emea Village.

The results of the study showed that the heavy metal content in Moahino Village was mercury (0.0036 mg/L) and lead (0.012 mg/L) indicates that the heavy metal content is above the threshold the quality standard value based on PPRI no. 22 in 2021. The results of the study showed that the heavy metal content in Ungkea Village was mercury (0.0018 mg/L) and lead (0.008 mg/L) indicates that the heavy metal content is above the threshold the quality standard value based on PPRI no. 22 in 2021. The results of the study showed that the heavy metal content in Emea Village was mercury (0.0079 mg/L), copper (0.009 mg/L), and lead (0.012 mg/L) indicates that the heavy metal content is above the threshold the quality standard value based on PPRI no. 22 in 2021.

Figure 6 show heavy metals in Bahodopi Waters. Based on Table 6 there are two villages that were used as sampling locations in Bahodopi Waters, namely Bahodopi Village 1 and Bahodopi Village 2.

The heavy metal content in Bahodopi Village 1 is very high and exceeds the threshold according to PPRI no 20 in 2021, as shown in Table 6. The heavy metal content of mercury (0.0024 mg/L), chromium (0.01 mg/L), copper (0.011 mg/L), and lead (0.013 mg/L). The heavy metal content in Bahodopi Village 2 is very high and exceeds the threshold according to PPRI no 20 in 2021, as shown in Table 6. The heavy metal content of mercury (0.0029 mg/L), chromium (0.02 mg/L), cadmium (0.002 mg/L), copper (0.012 mg/L), and lead (0.009 mg/L). The heavy metal content shown in Table 6 is the highest compared to the previous two stations. The main reason is that the mining industry is located around the waters of Bahodopi. The high content of heavy metals here is possible without aquatic biota which can survive. The results of the study from the three locations showed that the heavy metal content that exceeded the threshold based on PPRI no. 22 in 2021 was mercury (Hg), chromium (Cr), lead (Pb), cadmium (Cd), and copper (Cu). Mining activities produce heavy metals that are discharged into the waters after the washing stage. According to Siddiqua et al. [25], the continuous discharge of waste into coastal waters can have negative effects. The ongoing release of waste into coastal areas will result in the concentration and accumulation of these substances in the aquatic ecosystem. This process occurs if the heavy metals entering the waters are not dispersed by turbulence and ocean currents. The portion of the pollutant that is not diluted, dispersed, or carried away to the open sea will be absorbed or concentrated through biophysical-chemical processes. The heavy metals are then suspended in seawater (as floating sediment) and accumulate in the bottom sediment (settled sediment). Through biological processes, pollutants will enter the bodies of aquatic organisms via active absorption mechanisms (ion absorption and regulation) and through the food chain. According to Parui et al. [26], heavy metals can enter the tissues of living organisms through several pathways: the respiratory tract, digestion, and penetration through the skin. In animals, metals are absorbed into the bloodstream, bind to blood proteins, and are then distributed throughout the body's tissues. The highest accumulation of metals is usually found in the kidneys (excretion).

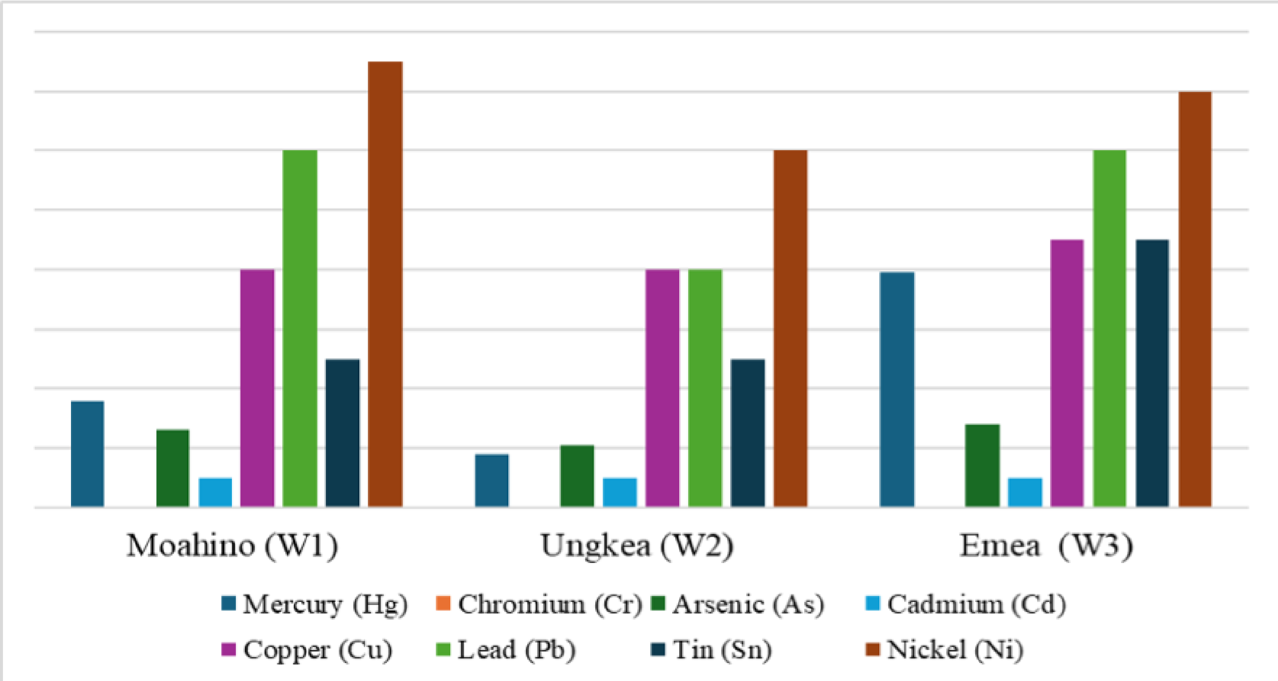

Figure 5. Profile of heavy metals in Wita Ponda Waters

Table 5. Heavy metals content in Wita Ponda Waters (mg/L)

Village	Mercury (Hg)	Chromium (Cr)	Arsenic (As)	Cadmium (Cd)	Copper (Cu)	Lead (Pb)	Tin (Sn)	Nickel (Ni)
Moahino (W1)	0.0036	<0.010	0.0026	0.001	0.008	0.012	<0.005	0.015
Ungkea (W2)	0.0018	<0.010	0.0021	0.001	0.008	0.008	<0.005	0.012
Emea (W3)	0.0079	<0.010	0.0028	0.001	0.009	0.012	0.009	0.014

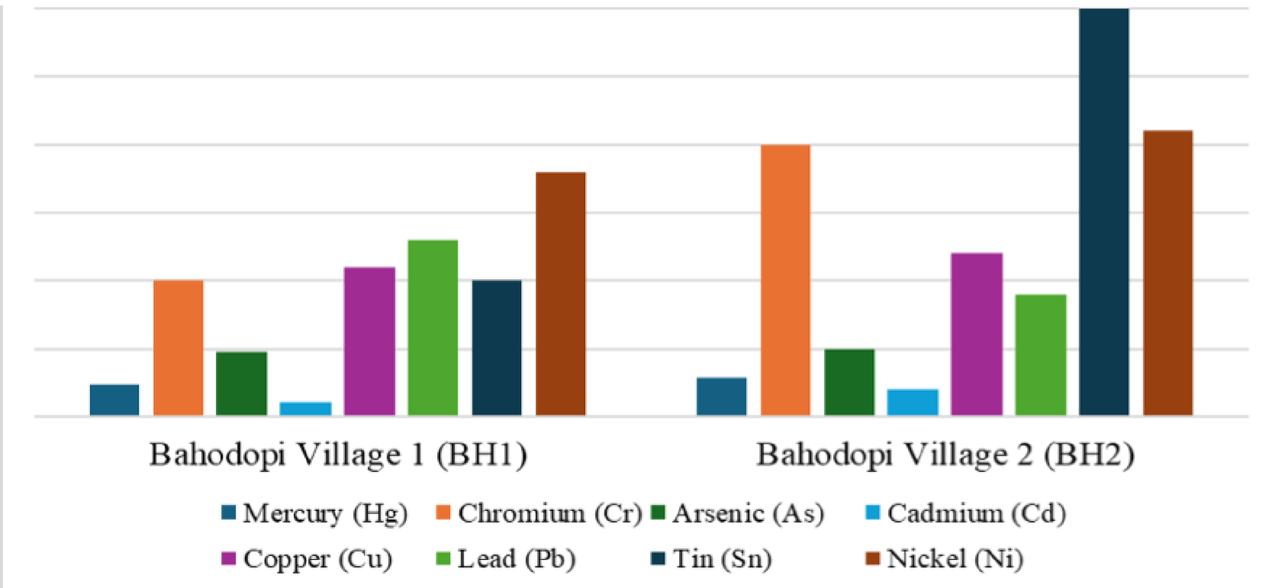

Figure 6. Profile of heavy metals in Bahodapi Waters

Table 6. Heavy metals content in Bahodopi Waters (mg/L)

Village	Mercury (Hg)	Chromium (Cr)	Arsenic (As)	Cadmium (Cd)	Copper (Cu)	Lead (Pb)	Tin (Sn)	Nickel (Ni)
Bahodopi Village 1 (BH1)	0.0024	0.01	0.0038	0.001	0.011	0.013	0.01	0.018
Bahodopi Village 2 (BH2)	0.0029	0.02	0.005	0.002	0.012	0.009	0.03	0.021

The nickel content in this study's results is still within the threshold and differs from the findings of Lestari et al. [27], which showed that the nickel (Ni) metal content in the bottom sediment of the waters in Fatufia Village, Bahodopi District, Morowali Regency, using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES), ranged from 778.84-1563.56 μg/g. The high nickel content is attributed to the station being located in a coastal area with mangrove vegetation, adjacent to the port terminal where nickel is stored and transported to ships, and near local residents' boarding houses. The difference in this study's results may be due to the lower nickel (Ni) metal levels at the tested station, likely caused by the area's openness and direct influence from the ebb and flow of seawater, despite its proximity to the port and docking areas for residents' boats. This is supported by the statement from Wali et al. [28], who explained that the high and low concentrations of nickel in sediment can be influenced by calm, relatively enclosed water conditions and proximity to nickel ore reservoirs (raw nickel materials).

A rising amount of studies links exposure to cadmium (Cd) to taste impairment, osteoporosis, renal failure, and malignancies in important organs. Early childhood development delays are also linked to lead (Pb) exposure [24]. High levels of heavy metal such as copper (Cu) and chromium (Cr) in marine biota, including seaweed, plankton, fish, and mollusks, can harm cells, interfere with phytoplankton's ability to photosynthesise, interfere with the operation of enzymes, and harm fish's liver and gills, among other essential organs. Through a process known as bioaccumulation, seaweed can absorb heavy metals from saltwater. Animals typically do not expel heavy metals that enter their bodies. as a result, the metal has a tendency to build up within the body [10]. As such, the metal is found at every stage of the food chain. When seaweed has a high chromium content, it can absorb a lot of heavy metal, which is afterward retained in the tissue of the plant. Higher levels of heavy metal, which are more dangerous, can harm seaweed's cell structure by impairing growth and reproduction processes, damaging cell membranes, and inhibiting enzymes involved in photosynthesis. Seaweed productivity declines accordingly.

Mercury is included in non-essential heavy metals that have toxic or toxic properties. Mercury is very dangerous if it enters the human body, although only in small amounts. Although mercury is available naturally in nature, mercury pollution in the ocean is still caused by human factors. Mercury metal (Hg) is a trace element with liquid properties at room temperature, specific gravity, and high electrical conductivity. Mercury is ranked as the most dangerous pollutant among various heavy metals. Other heavy metal elements can also potentially harm the aquatic environment. Industrial activities and natural activities cause the presence of mercury in the aquatic environment. The effect of mercury as a pollutant on marine life can be direct or indirect, for example, through decreased water quality and the food chain. The toxic form of mercury is methylmercury, which can be accumulated by aquatic biota. The accumulation process occurs in the fish's body because the mercury uptake (uptake rate) by fish is faster than the excretion process. The effect of mercury toxicity on fish can be lethal and sublethal, synergistic and antagonistic [29]. Mercury is a toxic metal harmful to all living organisms, even though it occurs naturally in the environment. For hazardous types of metal, just a few drops can produce fumes that can pollute the air in the room [19]. Mercury (Hg) is a trace element in the Earth's crust of about 0.08 mg/L and is only found in minimal amounts in natural waters. Mercury levels in the natural freshwater range from 10-100 nanograms/liter [9]. Mercury is the only metal that exists in liquid form at average temperatures. Mercury naturally occurs through metals, inorganic salts, and organic salts [30]. Inorganic salts and mercury can cause liver and kidney damage since the highest deposits of Hg in human "internal organs" occur in the liver and kidneys. The most dangerous component of mercury is methyl-mercury (organic mercury), which can cause the irreparable death of neurological disorders and genetic disorders. Compared to other mercury components, methylmercury components are less likely to be contaminated in the human body and are excreted slowly [10]. Table 7 below shows the contamination degree (Cdeg) of pollution and pollution load index (PLI) values at each sampling location.

The index of integrated contamination is a multi-element approach calculated based on a single contamination index. This study uses degree of contamination (Cdeg) values (Table 7). Contamination degree (Cdeg) reflects the cumulative impact of various contamination factors (Cf), indicating the overall heavy metal contamination level. We conducted a linear regression analysis between the contamination degree and the concentration of heavy metals in the sediment, as illustrated in Figure 7. Cdeg ranges from 7.26 - 36.33, showing the level of contamination ranging from low to high. The Cdeg value also indicates a low contamination level in sediment samples of 11% (Cdeg < 8), a moderate level of contamination of 33% (Cdeg between 8-16), a considerable contamination level of 22% (Cdeg of 16-32), and a high contamination level, because the Cdeg value is > 32 (33%) in South Bungku (BS2, BS3, and BS4).

The pollution load index (PLI) value serves to ascertain the contamination level of all observed heavy metals within the sediment samples across the coastal area of Morowali Regency. Additionally, we performed a linear regression analysis between the pollution load index and the concentration of heavy metals in the sediment to determine if the heavy metal concentrations increase with rising contamination degree and the Pollution Load Index, as shown in Figure 8.

Figure 8 shows the PLI value is between 0.18 - 0.53 because the average PLI value is <1, so it can be said that the sediment is uncontaminated with Cr, Cu, Pb, Hg, As, Ni, Sn, and Cd at all sampling locations.

Table 7. Values of Cdeg and PLI in sampling location

Sampling station	Cdeg	Classification of Cdeg	PLI	Classification of PLI
W1	8.84	Moderate	0.24	Uncontaminated
W2	10.15	Moderate	0.23	Uncontaminated
W3	7.26	Low	0.20	Uncontaminated
BH1	21.51	Considerable high	0.41	Uncontaminated
BH2	18.65	Considerable high	0.53	Uncontaminated
BS1	10.13	Moderate	0.23	Uncontaminated
BS2	36.18	High	0.19	Uncontaminated
BS3	35.32	High	0.21	Uncontaminated
BS4	36.33	High	0.18	Uncontaminated

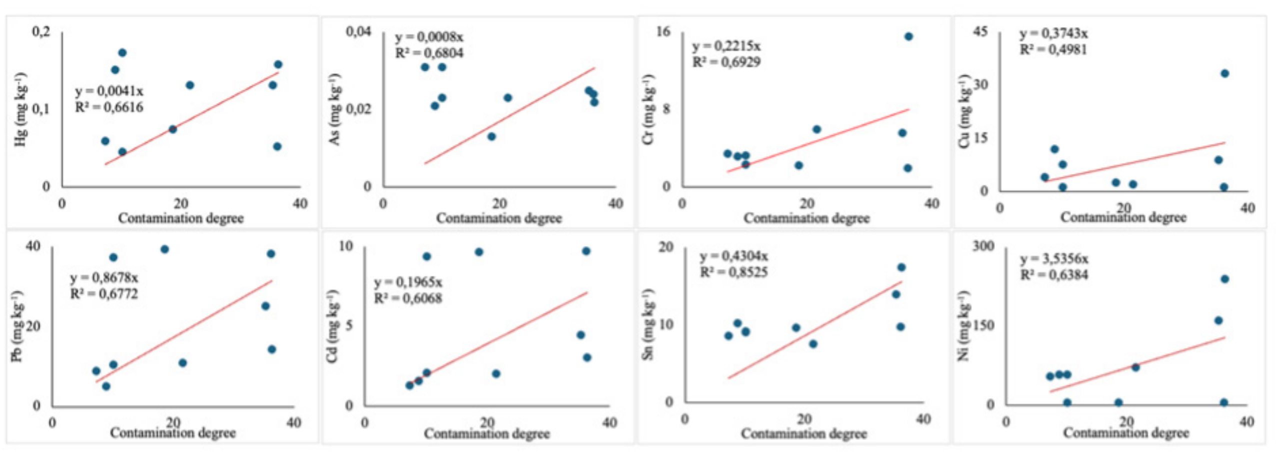

Figure 7. Linear regression analysis for the concentration of heavy metal within contamination degree (a) Hg (b) As (c) Cr (d) Cu (e) Pb (f) Cd (g) Sn (h) Ni

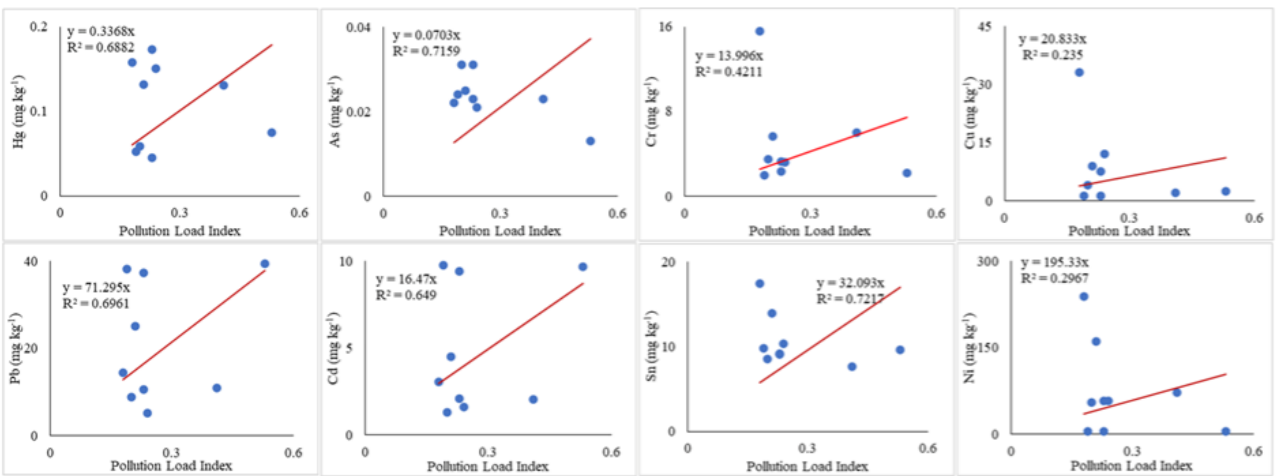

Figure 8. Linear regression analysis for the concentration of heavy metal within pollution load index (a) Hg (b) As (c) Cr (d) Cu (e) Pb (f) Cd (g) Sn (h) Ni

Impact on Ecosystem and Maritime Life in Morowali Waters

Morowali's waters lie within the coral biodiversity triangle, home to many threatened corals. Coral reefs are habitats for various marine resources of economic value. Thousands of families depend on these marine resources to make ends meet. Fishermen now have to go to sea farther than usual. Nickel mine waste damages coral reefs faster. Not to mention that wastewater runoff from the coal power plant of the IMIP area pollutes the nearby coast.

The land in Bahodopi, South Bungku, Pesisir Bungku, and other areas in Morowali Regency is rich in nickel. Nickel can easily be found on the surface of the land, along roads, both near coastal and forest areas. Small ports with ships docked show clear evidence of piles of ore (raw nickel material) forming hills, as if in a line. The forest cover, once green and dense, is now undergoing large-scale clearing. Thick and sharp dust blows like the aftermath of an 'atomic bomb' explosion when groups of trucks carrying ore (raw nickel material) cross steep mountain roads on their way to the ports. This condition has led to mass seaweed die-offs since 2014, signaling the threat of extinction for this commodity, which is an asset and icon of Central Sulawesi Province, particularly in Morowali Regency. The sea, which once supported aquatic life, is now filled with red soil from surrounding mountains, used as material for building nickel barge ports. The surge of nickel mining companies has caused rapid changes in the landscape of Morowali Regency. These changes are evident in critical areas projected as nickel hotspots, such as the Bahodopi coast toward South Bungku. The ecology and natural functions from Bahometefe District to Bahodopi have been significantly altered.

Nickel mining is like other extractive activities that greed for land and reduce the environment's carrying capacity. On land, deforestation has occurred since the last decade, which has caused primary forest areas to become increasingly eroded [31]. In the ocean, dumping by-products of mining activities threatens ecosystems and has the potential to pollute fisheries resources. So, mining activities make it difficult to avoid environmental pollution. According to Law No. 32 of 2009 concerning Environmental Protection and Management, environmental pollution is the entry or inclusion of living things, substances, energy, and other compounds into the environment by human activities to exceed the established environmental quality standards [32]. The concerns of environmental activists and researchers are increasingly evident that the green vehicle industry is sacrificing another environmental landscape, namely marine life. Furthermore, these projects will adversely affect small-scale fishermen or traditional fishermen who rely heavily on fishery resources in local waters.

In plain view, waste will make water conditions more turbid. Harmful metals can accumulate in the feeding chain of marine organisms and are very likely to accumulate in humans who consume them [33]. The potential for heavy metals contained in tailings can contaminate marine life. Heavy metals are relatively difficult to break down and tend to continue to accumulate in the food chain through the process of biomagnification. Tailings are mud left over when minerals are extracted from mine ore. Tailings contain rocks, chemicals, and elements that naturally become toxic when exposed to water or air. Tailings can spread and contaminate larger areas, especially damaging marine habitats and coral reefs [31]. Tailings waste disposal impacts the sedimentation of fish ecosystems in the sea, especially coral reefs as a place to forage and breed for fish. So that fishermen are disturbed in pursuing their livelihoods. In addition, sedimentation in mangrove ecosystems also damages crab corals [34]. Tailings waste disposed of in the deep sea has the potential to experience upwelling, and it is increasingly difficult to predict where it will settle back [31]. Mining companies can prevent hazardous waste or dispose of it more safely and less destructively using storage facilities with high safety standards.

Water, sediment, and living organisms can be used as indicators of the level of pollution that occurs. The toxicity of discarded tailings will affect the existing balance of life. For example, fish will experience periods of stress and eventually high mortality. As a respiratory organ and regulator of the osmoregulation system, it will be affected by waste toxicity [31]. In one study, a nickel mine in Papua New Guinea with sewage dumping into the sea still caused follow-on effects for up to three years after the closure of the project. The impact on the waters was 20 kilometers from the project center. The face of the water becomes reddened, causing mass fish death and increased heavy metal content.

Only some studies have analyzed the impact of nickel mining in the Morowali Regency area, especially on maritime conditions, except for observations made by the Central Sulawesi Forum for the Environment (WALHI). However, many case studies are similar to nickel mining objects that impact the surrounding sea conditions. Relevant policy makers in Morowali Regency should refer to previous studies or, more concretely, be able to conduct direct studies in the sea waters of Morowali Regency. Various options can be chosen instead of doing DSTD or direct discharge into the river flow that empties into the sea. For example, making tailings dams, making waste paste, or treating waste to be returned to the ground. Every plan to add mining facilities or production capacity should also consider the waste disposal plan. Being a strange thing that happens indicates the immunity of mining companies not to obey waste disposal rules. The progress of civilization without a maintained living environment will still cause disaster. Environmental awareness campaigns must continue to be carried out locally, nationally, and internationally. The sea is one of the regulated natural resources so that all Indonesians can utilize it as widely as possible. In this case, the government must regulate its utilization to control balanced utilization [35].

After the ore is extracted and separated on a global scale, mining operations generate millions of tons of mine tailing waste. Due to the presence of sulphates and some heavy metals, mine tailings are typically disposed of in environmentally controlled landfills. Additionally, they have a significant influence on our habitat that requires attention and significantly affect the length of the mine exploration activities. Since the production of cement involves significant energy requirements and high CO2 emissions (1 ton of cement may generate around 0.6 up to 1 ton of CO2 emissions, depending on the processing technology), the production of alkali-activated materials (AAM) and its derived products may constitute a waste management solution and a replacement for cementitious materials in specific applications, according to Paiva et al. [39]. Because of their qualities, including chemical endurance, alkali-activated materials, also known as geopolymers, have a wide range of uses as alternatives to regular Portland cement (PC) in specific applications. These materials can resist high temperatures and chemical attacks from salts and acids, and they can also increase mechanical qualities. A review of the possible use of geopolymerization for mine tailings consolidation was conducted by Feng Rao and Qi Liu [40]. They found that if mine tailings include the aluminosilicates needed for the polymerization reaction, geopolymerization reactions can effectively consolidate and reinforce them.

Seaweed Cultivation as a Livelihood in Morowali Regency

In general, coastal communities in Morowali Regency are generally classified as low-income. Most of these people make a living as fishermen because of the limited business land suitable for agriculture. Central Sulawesi Province is one of the producers of Seaweed. Currently, the government focuses on utilizing coastal resources to produce commodities of high economic value, such as Eucheuma cotton seaweed. This species has long been the main livelihood of the Menui Islands and South Bungku District coastal residents. Salabangka Islands, the largest seaweed producer in Morowali Regency, has good potential for seaweed cultivation, improving the welfare of coastal communities and expanding employment. However, preliminary information on the empowerment of coastal communities in this area through seaweed cultivation still needs to be widely known. Dried seaweed produced by communities in three districts (Morowali, Parigi, and Bangkep) is the final product of seaweed that has been processed into jelly.

Seaweed is a leading aquaculture commodity with competitive economic value in domestic and foreign markets. The seaweed cultivation business is not only a source of foreign exchange for the country and the income of cultivators; it can also absorb labor and utilize the potential coastal waters and the Indonesian archipelago [25]. The high potential utilization of seaweed globally has yet to be matched by maximum seaweed cultivation. The development of seaweed cultivation requires systematic efforts, especially in providing seeds, which are now increasingly constrained due to declining growth quality and global climate change. To support the production of high-quality and sustainable seaweed, it is necessary to develop superior seeds. The scarcity of seaweed seeds often occurs every year due to seasonal changes.

Seaweed farmers in Indonesia continue to grow and play a strategic role in national economic growth. Many fishermen then turned their professions into seaweed cultivators. Seaweed cultivation is easy and has relatively low investment [36]. Seaweed cultivation does not require high technology, investment tends to be low, absorbs quite a lot of labor, and generates relatively large profits. This business development is expected to reduce unemployment (pro-job), increase people's income (pro-growth), and, in turn, reduce poverty (pro-poor). Seaweed is a leading commodity with a prospective market [37]. Seaweed contains secondary metabolites that have potential as antimicrobials and antibiotics [38].

The existence of many companies in several regions in Central Sulawesi that contribute to water pollution, such as nickel mining, makes the landscape of Morowali Regency change pretty quickly. This is done at vital points projected as nickel mining hotspots in Bahodopito, South Bungku, and gravel mining in Palu Bay. High mining activity along the coast has changed seawater quality, affecting seaweed production. Seaweed needs sunlight to grow; sunlight is used as an energy source through photosynthesis by utilizing CO.

Organic fertilizers are growing today, and this cannot be separated from the impact of using inorganic fertilizers that cause various problems, ranging from damage to ecosystems, loss of soil fertility, and health problems to the farmer's dependence on fertilizers. Therefore, using organic fertilizers is again encouraged for Original Research Open Access 129 to overcome these problems. The addition of tea water waste containing nitrogen (N), phosphorus (P), potassium (K), and other nutrients such as iron (Fe), zinc (Zn), copper (Cu), calcium (Ca), and magnesium (Mg) in water media can meet the nutrients needed by seaweed for its growth.

CONCLUSION

The results showed several significant findings related to heavy metal contamination, which is suspected to cause mass deaths in seaweed cultivation in waters affected by mine waste. Heavy metal contents are often found to exceed the threshold for aquatic biota. Based on the results obtained, this research shows a significant increase in the content of heavy metals, such as mercury, arsenic, nickel, and lead, in waters affected by mining waste. The analysis showed that these heavy metal concentrations exceeded the permissible threshold for aquatic life. The highest concentration of heavy metals in Bahodopi Village 1 and Bahodopi Village 2. Visual indications such as reddish cat air and higher mud deposition in the area also prove this. Evidence indicates higher heavy metal contamination and a more impacted aquatic environment. Through a process known as bioaccumulation, seaweed can absorb heavy metals from saltwater. Animals typically do not expel heavy metals that enter their bodies. As a result, the metal tends to build up within the body. As such, the metal is found at every stage of the food chain. When seaweed has a high heavy metal content, it can absorb much heavy metal, afterwards retained in the plant tissue. Higher levels of heavy metals, which are more dangerous, can harm seaweed's cell structure by impairing growth and reproduction processes, damaging cell membranes, and inhibiting enzymes involved in photosynthesis. Seaweed productivity declines accordingly.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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