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Heavy Metal Bioaccumulation in Seagrass and Sargassum Across Indonesian Coastal Waters: Ecological Risks and Implications for Sustainable Coastal Management—A Systematic Review

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Abstract

Heavy metal contamination poses a significant threat to Indonesian coastal ecosystems, particularly seagrass meadows and brown seaweeds such as Sargassum, which function as primary producers and environmental bioindicators. This study systematically reviews heavy metal accumulation in seagrass and Sargassum in Indonesian waters and examines its ecological and management implications. A systematic literature review was conducted following the PRISMA 2020 framework, covering studies published between 2016 and 2025 from Scopus, ScienceDirect, Web of Science, Google Scholar, and Garuda. Articles were included if they reported empirical data on heavy metal contamination in seagrass or Sargassum in Indonesia. After screening and quality assessment, 20 studies were selected for thematic synthesis. The results show that lead (Pb) and cadmium (Cd) were the most frequently reported metals exceeding quality standards, identified in 14 of 20 studies. Mercury (Hg) was detected at several sites, while nickel (Ni) and iron (Fe) were mainly associated with mining areas. Higher accumulation was observed in seagrass leaves and Sargassum thalli, particularly in areas influenced by ports, industry, tourism, settlements, and mining. These findings indicate potential ecological risks, including reduced primary productivity and trophic transfer. Overall, seagrass and Sargassum demonstrate strong potential as biomonitors of heavy metal contamination in Indonesian coastal waters.

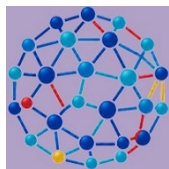
Keywords: bioaccumulation, biomonitoring, coastal management, heavy metals, sargassum

INTRODUCTION

Indonesia's coastal areas are highly dynamic and vulnerable to the pressures of human activity. The development of industrial areas, ports, coastal tourism, settlements, and mining has increased the input of various pollutants into marine waters, including heavy metals. The presence of heavy metals in coastal waters raises concerns because they are persistent, difficult to degrade, and can accumulate in environmental compartments. This condition has been demonstrated in Batam waters, where the heavy metals copper (Cu) and lead (Pb) were detected in various coastal environmental components (Ismarti et al., 2017).

Marine plants such as mangroves, seagrasses, and seaweeds offer significant benefits to life, both biologically, with antibacterial, anticancer, and antioxidant properties, and also serve ecological functions (Eka et al., 2024; Willian, 2018; Willian et al., 2021). Within the context of coastal ecosystems, seagrasses and seaweeds are biological components with crucial ecological roles. Seagrasses function as primary producers, sediment stabilizers, and habitat providers for various marine organisms. Several seagrass species are also known to possess a high capacity to absorb and accumulate heavy metals from the surrounding waters. This is demonstrated by the seagrass *Enhalus acoroides* in Sanur Waters, which





is able to accumulate zinc (Zn) in its tissues, thus reflecting the quality of the surrounding waters (Santanaa, 2018).

In addition to seagrass, brown seaweeds such as *Sargassum* also play a vital role in coastal ecosystem dynamics and socio-economic activities; they can be heavy metal monitoring tools (Eka et al., 2024; Willian et al., 2023; Fahrezi, Willian, 2025). *Sargassum* can absorb and accumulate heavy metals in its thallus through direct interaction with the water column. This is demonstrated in the waters of Awur Bay, Jepara, where *Sargassum* contains lead (Pb) from the surrounding waters (Malau et al., 2018). This demonstrates that seaweed has the potential to be a sensitive biological indicator of changes in coastal environmental quality.

The accumulation of heavy metals in seagrass and seaweed raises concerns not only for ecosystem sustainability but also for food security. Seaweed is widely used as food and industrial raw materials, so the presence of heavy metals in the tissues of these organisms has the potential to pose health risks to humans. This was seen in *Kappaphycus alvarezii* in Sumenep Regency, Madura, which contained Pb, Hg, and Cd in its thallus tissue (Afrianti et al., 2019). These findings indicate that heavy metal pollution can directly impact the health of coastal communities.

The dynamics of heavy metal pollution in Indonesian waters are also significantly influenced by variations in human activity in coastal areas. In mining areas, pollution pressure originates from runoff from extraction materials, which carry heavy metals into the waters. This is evident in Totok Bay, North Sulawesi, where gold mining activities contribute to the presence of various heavy metals in the water, sediment, and marine algae (Nasprianto, 2019). This situation indicates that the nature of heavy metal pollution pressure is significantly influenced by the type of coastal area use.

Although studies on heavy metal accumulation in seagrass and seaweed have been conducted in several Indonesian coastal regions, most remain site-specific and focus on individual metals, species, or local pollution sources. A systematic synthesis comparing accumulation patterns across regions, biota types, metal groups, and anthropogenic pressures is still limited. Therefore, this review addresses that gap by integrating evidence from studies conducted in Indonesian waters to identify dominant heavy metals, frequently affected organisms and tissues, ecological implications, and their relevance for risk-based coastal management

Based on these conditions, a systematic review of heavy metal accumulation in seagrass and *Sargassum* in Indonesian waters is highly relevant. A systematic literature review approach allows for a structured, objective, and evidence-based synthesis of scientific findings from various research locations. By integrating ecological implications and coastal management aspects, this study is expected to provide a stronger scientific basis to support the formulation of coastal management policies based on the risk of heavy metal pollution in Indonesia.

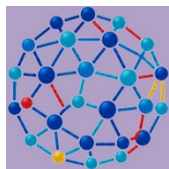
METHODS

This study employed a Systematic Literature Review (SLR) approach, adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. This method was chosen to obtain a comprehensive overview of the ecological conditions of *Sargassum* and seagrass in Indonesian waters and their relationship to heavy metal contamination, a key coastal environmental issue. The research process was carried out through several systematic stages:

1. Literature Search Strategy

The literature identification process was conducted systematically across several scientific databases, including Scopus, Science Direct, Web of Science, Google Scholar, and Garuda. To ensure broad search coverage, keywords were compiled using a Boolean Operator approach: (“*Sargassum*” AND “Indonesia” AND “heavy metal”) OR





("Sargassum" AND "Indonesia" AND "bioaccumulation") OR
("seagrass" OR "lamun" AND "Indonesia")
AND "heavy metal") OR
("seagrass" OR "lamun" AND "Indonesia")
AND "pollution") OR
("macroalgae" AND "Indonesia" AND "heavy metal").

The initial search identified 54 records. After removing one duplicate, 53 records were screened based on titles, abstracts, and keywords. Eighteen records were excluded because they were not thematically relevant. The remaining 35 full-text articles were assessed for eligibility, of which 15 were excluded because they discussed seagrass or seaweed ecology without specific heavy metal contamination data. Finally, 20 articles met all inclusion criteria and were included in the qualitative synthesis.

2. Inclusion and Exclusion Criteria

Literature selection was conducted based on predetermined inclusion and exclusion criteria. Inclusion criteria included: (1) research conducted in Indonesian waters; (2) the study object was Sargassum or seagrass; (3) the article discussed aspects of ecology, community structure, biomonitoring, or heavy metal pollution; and (4) the article was published as a full paper in a scientific journal. Articles were excluded if: (1) they were not related to the Sargassum or seagrass ecosystem; (2) they were conducted outside of Indonesia; (3) they did not present empirical data; or (4) they were opinion pieces, editorials, or non-scientific reports.

3. Screening and Eligibility Evaluation Stage

All articles obtained during the identification stage were then screened through a review of titles, abstracts, and keywords. At this stage, 18 articles were eliminated due to a lack of thematic relevance. A further 35 articles were evaluated through a full-text review to assess methodological suitability and data completeness. The evaluation results indicated that 15 articles were relevant in the ecological context of Sargassum or seagrass but did not address heavy metal contamination. The remaining 20 articles met all primary inclusion criteria because they explicitly examined heavy metal contamination of Sargassum or seagrass in Indonesian waters.

A methodological appraisal was conducted before final inclusion. Each article was assessed based on five criteria: relevance to the review objective, clarity of study location and organism, clarity of analytical method for heavy metal determination, availability of concentration data or comparison with quality standards, and relevance to ecological or coastal management interpretation. Articles that did not provide empirical heavy metal data or lacked sufficient methodological clarity were excluded from the final synthesis

4. Data Synthesis

Articles that passed the final selection process were then qualitatively analyzed to identify thematic patterns, geographic scope, methodological differences, and reported levels of heavy metal contamination. The synthesis process emphasized the consistency of findings across studies and their relevance to sustainable coastal ecosystem management. A total of 20 articles were used in the final synthesis. The complete literature selection process is presented in the PRISMA flow diagram in Figure 1



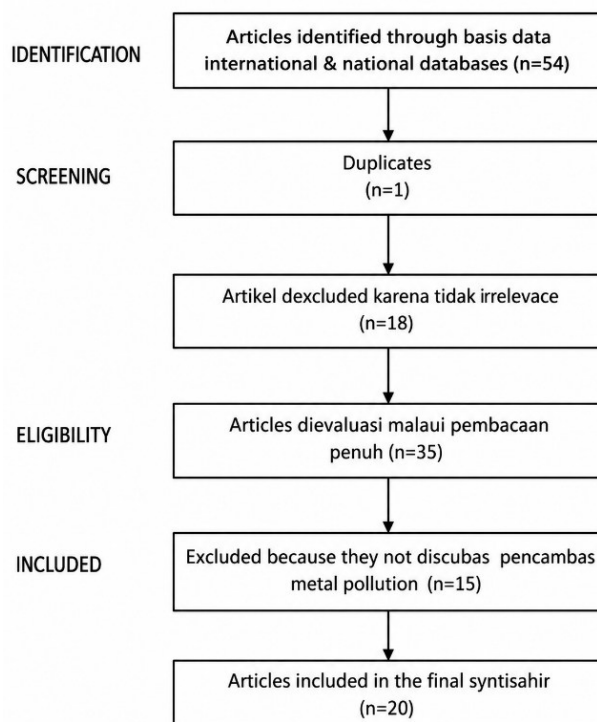
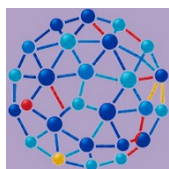


Figure 1. PRISMA flow diagram of literature identification, screening, eligibility assessment, and final inclusion

RESULTS AND DISCUSSION

The accumulation of heavy metals in seagrass and Sargassum in Indonesian waters reveals important environmental issues in the context of coastal management. The patterns found indicate that human activities play a significant role in increasing levels of heavy metals such as Pb, Cd, Cu, Zn, and others. A synthesis of 20 articles shows that research on heavy metal accumulation in seagrass and Sargassum in Indonesian waters has increased over the past decade and is widespread in Java, Bali, Sumatra, Sulawesi, Papua, and Nusa Tenggara. These locations represent coastal areas with high anthropogenic pressure, such as ports, industrial areas, coastal tourism, dense settlements, and mining areas. These findings indicate that heavy metal contamination is a recurring issue across several Indonesian coastal regions represented in this review, particularly in areas affected by ports, industry, settlements, tourism, and mining. The proportion of research locations with heavy metal levels exceeding quality standards (n=20) is shown in Figure 1.



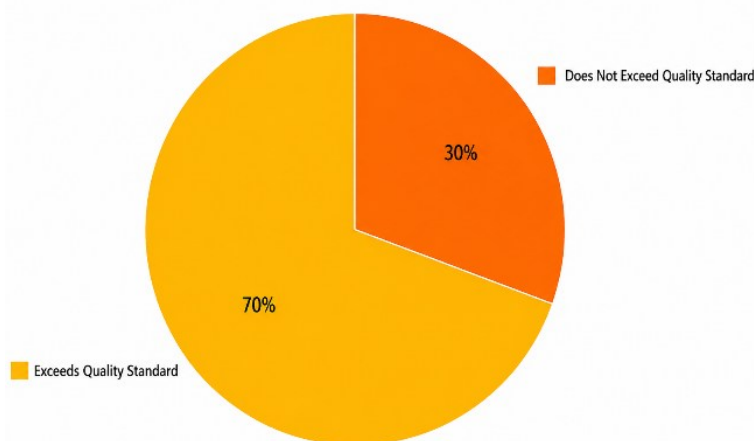
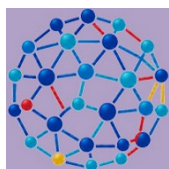


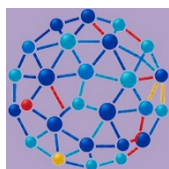
Figure 2. Proportion of Heavy Metal Content in Standard Quality (Data Source: Processed results from various journals)

Figure 2 indicates that 70% of the reviewed studies reported metal concentrations exceeding the quality standards or benchmarks used in the respective studies. This pattern does not imply uniform pollution across all Indonesian coastal waters, but it suggests that studies conducted in areas with intense anthropogenic pressure tend to report higher exceedance. Therefore, the finding should be interpreted as evidence of elevated risk in the studied coastal hotspots rather than as a complete national assessment.

Heavy metal concentrations that exceed the quality standards include: 1) Industrial and port activities that cause: Metal industrial waste, ship paint, shipyards, and fuel often contain Pb, Cu, and Cd. Locations such as Batam and Banten Bay show high Pb levels due to shipping and ship maintenance activities. 2) Mining in coastal areas and upstream rivers is a source of Gold and nickel mining in areas such as Totok Bay (North Sulawesi) and Morowali, which releases Hg, Ni, and Fe into rivers and coasts, and Mine sediment runoff causes heavy metals to accumulate on the seabed. 3) Domestic waste and dense coastal settlements cause untreated household wastewater (soap, detergent, batteries, and electronics) to increase the content of heavy metals, especially Pb and Cd. 4) Intensive agriculture and fisheries in using fertilizers, pesticides, and fish feed additives containing Zn and Cu, which can accumulate in water and marine biota, 5) Uncontrolled coastal tourism produces hotel waste, tourist boat maintenance, and cruise ship traffic in areas such as the Seribu Islands, increasing the content of heavy metals in the water column.

To overcome this problem, steps need to be taken, including: 1) Controlling pollution sources on land by implementing a zero discharge policy for industries adjacent to the coast and requiring wastewater treatment plants (IPAL) for industries and ports. 2) Managing mining waste and reclaiming former mining areas, implementing a tailings management system with international standards and using metal-absorbing vegetation (phytoremediation) in river basins before reaching the sea. 3) Strengthening biota-based water quality monitoring, monitoring is carried out using seagrass (*Enhalus acoroides*, *Ralassia hemprichii*) and Sargassum as natural biomonitors for early detection of pollution, and integrating biomonitoring data into the national environmental information system. 4) Arranging coastal settlements, the arrangement is carried out by providing an integrated sanitation system and community-based waste management to reduce domestic waste and educating the public about the dangers of disposing of batteries and electronics into the sea. 5) Rehabilitate coastal ecosystems by replanting seagrass and mangroves as natural biofilters for absorbing heavy metals and encouraging the conservation of areas with low anthropogenic pressure as protected zones. 6) Policy and law





enforcement, carried out by strengthening supervision of violations of environmental quality standards through administrative and legal sanctions, and integrating heavy metal data in the spatial planning of coastal areas and small islands (RZWP3K).

This proportion indicates that the majority of the study sites are under relatively high pollution pressure. Ecologically, this condition indicates that the accumulation of heavy metals in seagrass and *Sargassum* is not a sporadic occurrence, but has become a fairly common phenomenon in Indonesian coastal waters. This finding also reinforces the urgency of strengthening biota-based water quality monitoring systems as part of sustainable coastal management. The distribution of dominant heavy metals at the study sites can be seen in Figure 3.

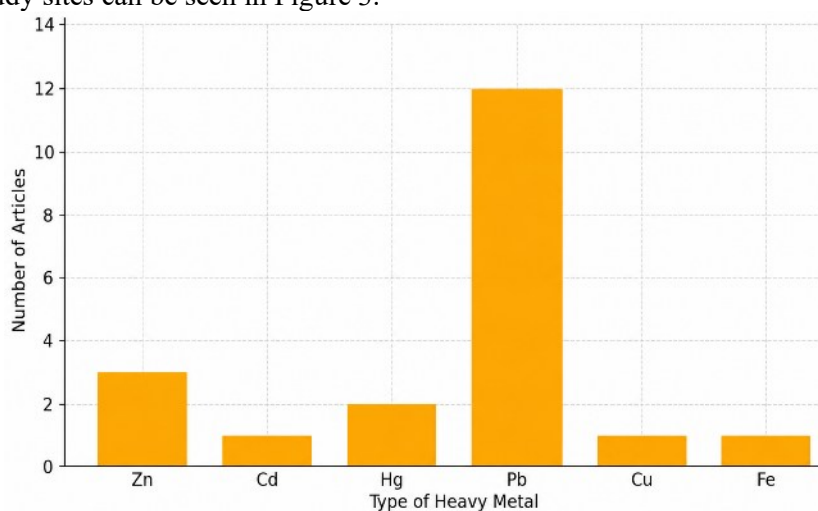


Figure 3. Distribution of Dominant Heavy Metals at the Research Location
(Data Source: Processed results from various journals)

Based on the dominant heavy metal distribution graph, lead (Pb) is the type of heavy metal most frequently reported as a major pollutant in the 20 articles reviewed. The dominance of Pb indicates that this metal remains a major pollutant in Indonesian coastal ecosystems, especially those related to port activities, industry, and coastal settlements. In addition to Pb, other heavy metals that are also frequently found are zinc (Zn), which is found in tourist sites, gold mines, and industry. This is influenced by the determining factors of the type of anthropogenic activity, ocean current systems, and the presence of metal-absorbing vegetation and cadmium (Cd), which are generally related to anthropogenic activities in coastal and inland areas.

Mercury (Hg), copper (Cu), and nickel (Ni) were found at lower frequencies, but their presence remains a concern because they are toxic and have the potential to accumulate in biota tissues. This pattern indicates that heavy metal pollution in Indonesian waters is not dominated by only one type of metal, but is the result of a combination of various pollutant sources with different characteristics. The distribution based on the type of biota that is most frequently studied in the articles can be seen in Figure 4.



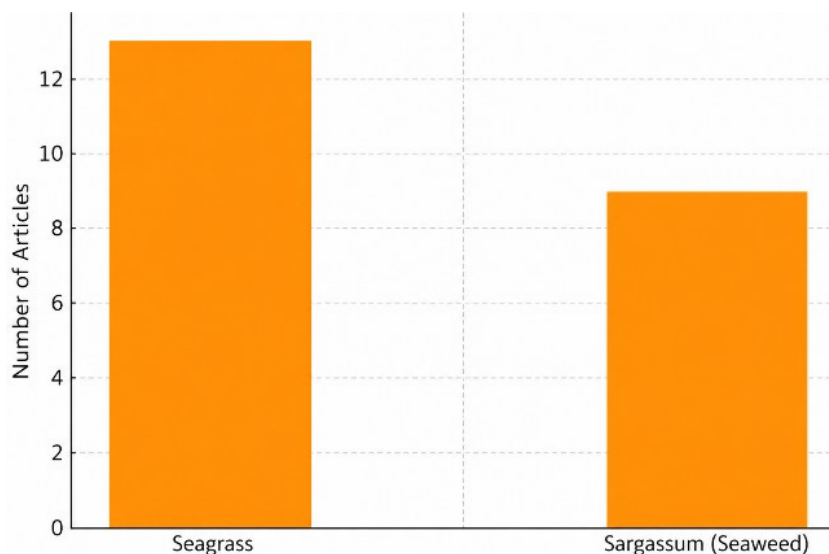
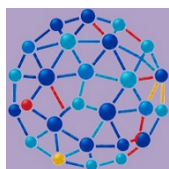


Figure 4. Distribution Based on Types of Biota Most Researched in the Article

The biota distribution graph shows that of the 20 articles reviewed, 11 focused on seagrass, while the other 9 articles examined seaweed, particularly *Sargassum* and other macroalgae. This pattern indicates that seagrass remains the primary object of study of heavy metal pollution in Indonesian coastal waters, due to its role as a primary producer and sensitive environmental bioindicator. However, the nearly equal proportion of research on *Sargassum* indicates increasing attention to seaweed as an ecological and economic commodity vulnerable to heavy metal pollution. This balance of research focus confirms that both types of biota play a strategic role in detecting and understanding the dynamics of heavy metal pollution in Indonesian coastal ecosystems.

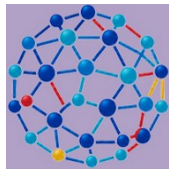
Sargassum (brown seaweed) and seagrass (seagrass) play a crucial role as natural bioindicators due to their ability to absorb heavy metals (Pb, Cd, Hg, Ni, Zn, Fe, etc.) from seawater, sediment, and surrounding organic matter. Seagrass leaf tissue and *Sargassum* thallus have a high capacity to absorb and accumulate heavy metals due to their direct contact with the water column and large surface area. This makes them passive and active metal absorbers through the adsorption and absorption of metal ions, a condition shown to vary spatially.

In Bayur Bay, Pb and Cu levels are still within safe limits for consumption and the environment (Fitri et al., 2021). However, in Awur Bay, Lombok, and Lamongan, Pb and Cd levels in *Sargassum* and *Caulerpa* have exceeded established quality standards, potentially posing environmental and health risks (Astriani et al., 2024; Malau et al., 2018; Safitri et al., 2023). This difference confirms that local water quality conditions significantly determine the ecological and food safety of seaweed.

These differences in pollution status are closely related to the intensity of human activity in each region. In Batam and Banten Bay, high accumulations of Pb and Cu in seagrass are associated with shipyard activities, ports, and domestic waste (Ismarti et al., 2017; Falah et al., 2020). In the Seribu Islands and Sembilan Islands, the main sources of pressure come from ship traffic, tourism, and coastal settlements (Rosalina et al., 2022; Triyanto et al., 2024). Meanwhile, in Totok Bay and Morowali Bay, gold and nickel mining activities are the dominant factors explaining the high accumulation of Cd, Pb, Hg, Ni, and Fe in algae and sediments (Lestari et al., 2024; Nasprianto, 2019). In contrast, areas with relatively more controlled coastal management, such as Sanur and Teluk Bayur, show heavy metal levels that tend to remain within safe limits (Fitri et al., 2021; Santanaa, 2018).

Despite differences in location and type of metal, all articles show a relatively consistent pattern





regarding the organism parts with the highest accumulation. Seagrasses, particularly *E. acoroides* and *T. hemprichii*, have the highest heavy metal concentrations in the leaves compared to the roots and rhizomes (Falah et al., 2020; Triyanto et al., 2024) In *Cymodocea*, several locations also show high accumulation in the roots (Sembel et al., 2021). Seaweeds, including *Sargassum*, *Gracilaria*, *Caulerpa*, and *Kappaphycus*, have the highest heavy metal accumulation in the thallus (Afrianti et al., 2019; Ardiyansyah et al., 2019). In mining areas, Ni and Fe accumulate predominantly in the sediment Lestari (Lestari et al., 2024). This pattern suggests that organism organs that interact directly with the water column and have a high surface area are the primary sites for heavy metal accumulation.

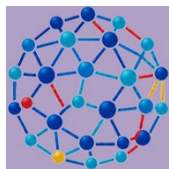
The accumulation of heavy metals in physiologically active tissues has significant ecological implications. Seagrass leaves, as the center of photosynthetic activity, are highly susceptible to disruptions due to exposure to Pb, Cd, and Hg, which can reduce photosynthetic efficiency and inhibit growth (Falah et al., 2020; Rosalina et al., 2022). Changes in chlorophyll levels and disruption of cell structure due to heavy metal exposure have been reported in seaweed, *Kappaphycus* (Afrianti et al., 2019). These disruptions at the primary producer level have the potential to reduce the overall productivity of coastal ecosystems.

Table 1. Characteristics of 20 Studies–Heavy Metal Accumulation in Seagrass & Sargassum

No	Author (Year)	Location	Object	Type of Metal	Key Findings (Quality Standard & Peak Accumulation)
1	Ismarti (2017)	Batam	<i>E. acoroides</i>	Cu, Pb	Exceeds; peak in leaves
2	Malau (2018)	Jepara	<i>Sargassum</i>	Pb	Exceeds; peak in sediment & thallus
3	Santana (2018)	Sanur, Bali	<i>E. acoroides</i>	Zn	Does not exceed; peak in leaves
4	Supriyantini (2016)	Jepara	<i>Enhalus, Ralassia</i>	Zn	Does not exceed; peak in leaves
5	Ardiyansyah (2019)	Sidoarjo	<i>Gracilaria</i>	Cd	Exceeds; peak in thallus
6	Afrianti (2019)	Sumenep	<i>Kappaphycus</i>	Pb, Hg, Cd	Exceeds; peak of Hg & Cd in thallus
7	Nasprianto (2019)	Totok– Blongko	<i>Halimeda</i>	Cd, Pb, Zn, Hg	Exceeds; peak in Totok tissue
8	Putra (2019)	Jepara	<i>E. acoroides</i>	Zn	Partially exceeds; peak in leaves
9	Putra (2020)	Banten Bay	<i>E. acoroides</i>	Pb	Exceeds; peak in tissue
10	Fitri (2021)	Bayur Bay	<i>Sargassum</i>	Pb, Cu	Does not exceed; peak in thallus
11	Sembel (2021)	Manokwari	<i>Cymodocea</i>	Pb, Cd, Cu, Cr(VI)	Exceeds; peak in roots
12	Rosalina (2022)	Sembilan Island	<i>Ralassia, Enhalus</i>	Pb, Cd	Exceeds; peak of Pb in leaves
13	Bayu (2022)	Banyuwangi	<i>E. cottonii</i>	Pb, Cd, As	Does not exceed; peak in thallus
14	Rosiana (2022)	Sanur, Bali	<i>Sargassum et al.</i>	Pb, Cd, Hg, As	Does not exceed; thallus is the main indicator
15	Safitri (2023)	Lamongan	<i>Caulerpa</i>	Pb	Exceeds; peak in thallus
16	Putra (2023)	Sekotong, Lombok	Seagrass	Hg	Exceeds sediment standard; peak in sediment
17	Triyanto (2024)	Seribu Islands	<i>T. hemprichii</i>	Pb	Exceeds water standard; peak in leaves
18	Astriani (2024)	Lombok	<i>Sargassum</i>	Pb, Cd	Exceeds SNI (National Standard); peak in flour
19	Lestari (2024)	Morowali	Sediment	Ni, Fe	Exceeds; peak in sediment
20	Gusri (2025)	Pahawang, Lampung	<i>Cymodocea, Ralassia</i>	Pb, Cu, Ni, Zn	Does not exceed; peak in leaves

These ecological implications subsequently lead to risks to the coastal food chain. The accumulation of heavy metals in seagrass and seaweed opens up the opportunity for metal transfer to





higher trophic levels through consumption mechanisms by herbivores and intermediate organisms. This condition is a serious concern in areas that utilize seaweed as a food ingredient, such as Lombok and Lamongan, where Pb and Cd levels have exceeded consumption quality standards (Astriani et al., 2024; Safitri et al., 2023). Conversely, at Sanur Beach, the results of the study showed that heavy metal levels in seaweed were still within safe limits for human health because in seagrass and seaweed at Sanur Beach, no heavy metal clusters were detected in the FTIR analysis. Chemical values approached the Food Chemical Codex (FCC) standards, which indicates a high level of purity and the relatively clean condition of Sanur waters from large industrial activities that are the main source of heavy metal contamination (Permatasari et al., 2022).

From a coastal management perspective, these findings demonstrate the potential for use as bioindicators of heavy metal pollution. The consistent finding that Pb and Cd levels frequently exceed quality standards in areas with high anthropogenic pressure reinforces the urgency of integrating biota-based biomonitoring into water quality monitoring systems. At the same time, areas that remain within safe limits can serve as initial models for more sustainable coastal management practices.

Overall, this review confirms that heavy metal accumulation in seagrass and Sargassum in Indonesian waters is spatially distributed, strongly influenced by anthropogenic pressure, and exhibits the highest accumulation patterns in seagrass fronds and seaweed thallus. Lead (Pb) and cadmium (Cd) were the dominant pollutants most frequently exceeding quality standards, followed by mercury at certain locations, and nickel (Ni) and iron (Fe) in mining areas. These findings strengthen the position of seagrass and Sargassum as strategic biological indicators for monitoring coastal environmental quality and provide a scientific basis for formulating risk-based coastal management policies in Indonesia. However, due to the limited number of reviewed articles, uneven regional coverage, and variation in analytical methods and quality standards, the findings should be interpreted cautiously as a qualitative synthesis rather than a comprehensive national assessment.

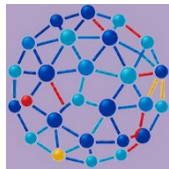
CONCLUSION

This systematic review indicates that heavy metal accumulation in seagrass and Sargassum has been reported across several Indonesian coastal regions, particularly in areas influenced by ports, industrial activities, settlements, tourism, and mining. Among the 20 reviewed studies, Pb and Cd were the most frequently reported metals exceeding the quality standards or benchmarks used in the respective articles, while Hg, Ni, and Fe were reported in specific mining-influenced areas. Accumulation was commonly observed in seagrass leaves and seaweed thalli, supporting their potential role as biomonitoring matrices for coastal heavy metal contamination. However, this review is limited by the relatively small number of studies, uneven regional coverage, and variation in analytical methods and quality standards. Therefore, the findings should be interpreted as a qualitative synthesis of reported patterns rather than a complete national assessment. Despite these limitations, the results support the integration of seagrass- and seaweed-based biomonitoring into risk-based coastal water quality management in Indonesia.

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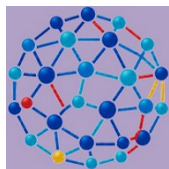




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