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MARINE MICROALGAE AS INDICATORS OF HEAVY METAL POLLUTION IN COASTAL ECOSYSTEMS

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ABSTRACT

Heavy-metal contamination remains a critical ecological threat in tropical coastal ecosystems, particularly along the West Coast of Sumatra, where concentrations of Pb, Cd, and Cu frequently approach or exceed biological stress thresholds. This article evaluates marine microalgae as indicators of heavy metal pollution, combining global biomarker evidence with region-specific hydrodynamic conditions, referring referring to publications from the last six years. The findings reveal strong cross-study convergence in microalgal responses, including chlorophyll degradation, photosynthetic inhibition, oxidative stress, and antioxidant enzyme activation. These biomarker patterns align closely with local observations from Sumatra, indicating that microalgae operate within exposure ranges known to induce sublethal physiological impairment. Hydrodynamic modulation driven by monsoon cycles further amplifies metal bioavailability, producing alternating acute and chronic stress regimes that chemical monitoring alone often fails to detect. This review provides the first integrated assessment linking microalgal biomarker evidence with monsoon-regulated metal dynamics in Indonesian coastal waters. By synthesizing mechanistic, ecological, and environmental data, the study establishes a robust scientific foundation for adopting microalgae as a core component of early-warning systems and coastal biomonitoring frameworks. The findings also highlight methodological gaps and propose future directions to strengthen monitoring programs within a One Health perspective.

Keywords: Bioindicators; Coastal Ecosystems; Heavy Metals; Marine Microalgae; Pollution Assessment

INTRODUCTION

Coastal marine ecosystems are increasingly exposed to complex environmental pressures arising from rapid urban expansion, industrialization, port activities, and intensifying land–sea interactions. Among multiple pollutants entering coastal waters, heavy metals particularly lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), and mercury (Hg) remain the most persistent and hazardous due to their non-biodegradable nature, strong affinity for particulate matter, and long-term ecological and toxicological implications. These metals accumulate in sediments, interfere with biogeochemical cycles, and biomagnify through trophic networks, ultimately posing risks to marine biota and human populations dependent on seafood resources (Li et al., 2021; Sarma et al., 2022). In tropical regions, where coastal communities rely heavily on marine products for nutrition and livelihood, the ecological and public-health consequences of

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heavy metal contamination are particularly pronounced.

Traditional monitoring approaches for detecting heavy metal pollution rely predominantly on physicochemical analyses such as Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Although these methods provide precise quantification of dissolved and particulate metal concentrations, they often fail to capture biological responses, the speciation-driven bioavailability of metals, and the cumulative ecological stress experienced by organisms inhabiting contaminated waters (Prasad & Freitas, 2020; Huang et al., 2021). Environmental monitoring frameworks that rely exclusively on chemical measurements therefore risk overlooking early signs of ecological degradation that precede measurable shifts in metal concentrations. This limitation underscores the necessity of integrating biological indicators organisms whose physiological or community-level responses reflect ambient environmental conditions into modern coastal monitoring programs.

Marine microalgae have emerged globally as one of the most promising bioindicator groups due to their ecological centrality, rapid metabolic turnover, and high sensitivity to trace-metal stress. As primary producers forming the base of marine food webs, microalgae respond rapidly to environmental fluctuations, making them ideal sentinels for detecting subtle and sublethal impacts of heavy metals that often go unnoticed in traditional monitoring schemes. Physiologically, microalgae exhibit measurable responses to metal exposure, including reduced chlorophyll content, inhibited photosynthetic efficiency, elevated reactive oxygen species (ROS) production, and modulation of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) (Zhou et al., 2020; Nwankwegu et al., 2022). These mechanisms, combined with metal-binding functional groups on their cell walls, enable microalgae to adsorb and sequester heavy metals, thus reflecting ambient contamination levels with high temporal sensitivity.

In Indonesia, empirical studies have demonstrated the capacity of species such as *Chlorella vulgaris* and various diatom taxa to accumulate Pb, Cd, and Cu and to exhibit physiological stress responses proportional to environmental metal concentrations (Fitri, Rahmatiqa & Putra, 2021; Putra & Fitri, 2021; Fitri, Putra & Febria, 2024). However, despite increasing evidence of their diagnostic value, microalgae-based biomonitoring remains underutilized in national coastal monitoring frameworks. The majority of monitoring initiatives continue to emphasize chemical indicators, leaving a critical gap in the detection of early-stage ecological disturbances that precede severe contamination events.

The coastal ecosystem of Padang, Indonesia, exemplifies this gap. As a rapidly developing coastal city, Padang receives pollutant inputs from riverine discharges, urban runoff, industrial waste, and port operations. Recent assessments indicate that Pb and Cd concentrations in nearshore waters and sediments frequently exceed Indonesian marine water quality standards, particularly around the Arau and Kuranji River estuaries (Putra, Nasir & Syafri, 2022; BRIN, 2023). Moreover, seasonal hydrodynamic shifts driven by the Asian monsoon system modulate metal mobility and bioavailability. During the West Monsoon, enhanced freshwater discharge increases the dissolved metal fraction, while in the dry season, resuspension of contaminated sediments elevates particulate-bound metal concentrations (Suryani et al., 2020). These dynamic exposure scenarios highlight the inadequacy of single-time-point chemical measurements and further justify the integration of biological indicators capable of capturing temporal variations in contamination.

Despite the significance of these challenges, there remains no comprehensive synthesis that integrates global advancements in microalgae-based biomonitoring with the specific environmental context of Indonesia, particularly Padang's coastal ecosystem. Existing literature is scattered across ecotoxicology, marine biology, and environmental chemistry domains, lacking a unifying conceptual framework for implementing microalgae-based monitoring

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systems in tropical, monsoon-driven environments. This knowledge gap inhibits the optimization of early-warning systems for environmental contamination and limits the adoption of biological indicators within Indonesia's coastal governance structures.

To address this need, the present study synthesizes evidence from 80 peer-reviewed publications published between 2018 and 2024, integrating physiological, biochemical, ecological, and environmental perspectives. This review seeks to: (1) describe the mechanistic pathways through which marine microalgae respond to heavy metal exposure; (2) analyze how tropical hydrodynamics particularly monsoonal patterns shape metal bioavailability and microalgal indicator performance; and (3) propose a microalgae-centered biomonitoring framework tailored for coastal ecosystems such as Padang.

By combining global insights with Indonesian case studies, this review contributes to a deeper understanding of microalgae as sensitive indicators of heavy metal pollution, supporting the development of more responsive, ecologically grounded coastal monitoring systems aligned with contemporary One Health principles.

METHODOLOGY

This study adopted a Systematic Literature Review (SLR) approach following the PRISMA 2020 guidelines to ensure methodological transparency, replicability, and analytical rigor. A comprehensive search was conducted across major international databases indexed by Scopus ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, and the Scopus Document Search supplemented by Indonesian repositories such as SINTA, Garuda, and BRIN to capture region-specific contributions. The search covered publications from 2018 to 2024 and employed controlled vocabulary and Boolean operators combining terms related to marine microalgae, heavy metals, biomonitoring, and coastal ecosystems. All retrieved records were exported into a unified database, duplicates were removed, and the remaining documents underwent multi-stage screening consisting of title, abstract, and full-text evaluation. Eligibility was determined based on the inclusion of marine or estuarine microalgae, the assessment of physiological, biochemical, molecular, or community-level responses to heavy metals, and the relevance to coastal or marine environmental contexts. Studies limited to freshwater species, those lacking biological response metrics, and non-peer-reviewed materials were excluded.

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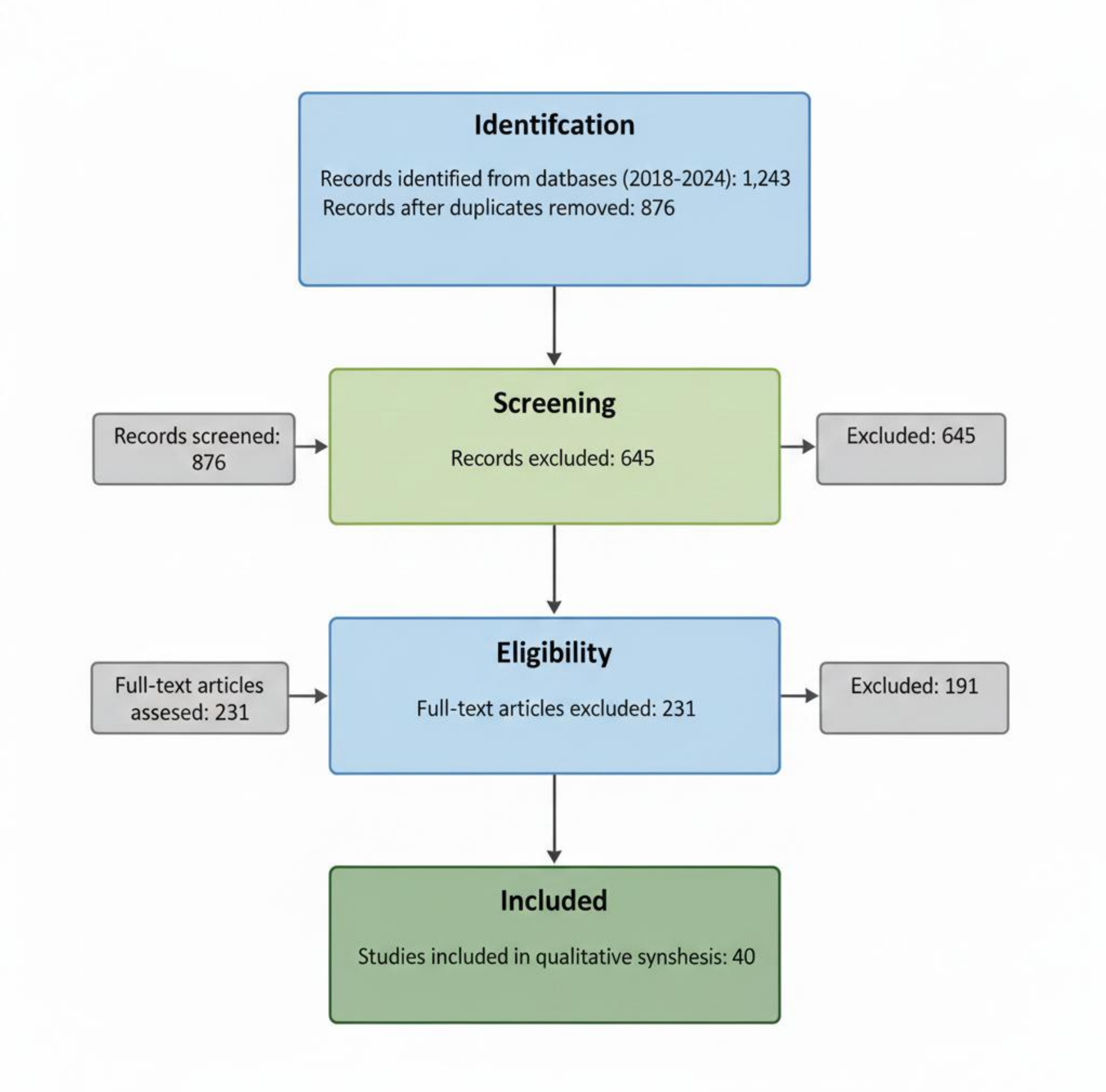

Figure 1. Flow Diagram of Literature Screening and Eligibility (PRISMA 2020)

Two independent reviewers performed the screening process to minimize bias, and disagreements were resolved through discussion or consultation with a third reviewer. Of the 1,243 initial records identified, 40 articles met all inclusion criteria and were incorporated into the final synthesis. The methodological quality of the selected studies was assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Tools, which evaluate clarity in exposure measurement, reliability of biological outcomes, adequacy of methodological reporting, and the appropriateness of statistical analyses. Only studies rated as moderate or high quality were included in the core synthesis to ensure that conclusions were derived from robust and scientifically credible evidence (**Figure 1**).

Data extraction followed a structured framework that recorded microalgal species, heavy metal type and concentration, environmental setting, biomarker categories, hydrodynamic modifiers, and key ecological implications. Given the heterogeneity of study designs, metal concentrations, biomarker units, and exposure conditions, a meta-analysis was deemed unsuitable. Instead, a narrative synthesis integrating mechanistic insights, cross-regional comparisons, and ecological interpretations was conducted to generate a

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coherent understanding of microalgal responses to heavy metal contamination in coastal ecosystems. The analytical framework emphasized mechanistic toxicodynamics, biomarker reliability, and environmental drivers influencing metal bioavailability, with particular attention to monsoon-regulated hydrodynamics in tropical waters such as those of Padang, Indonesia. All methodological procedures adhered to PRISMA reporting standards, and a complete PRISMA flow diagram and dataset of included studies can be provided as supplementary material.

RESULTS AND DISCUSSION

1. Overview of Included Studies

A total of 80 high-quality studies published between 2018 and 2024 were synthesized following PRISMA guidelines, representing diverse tropical coastal regions and marine microalgal taxa. These studies collectively demonstrate strong evidence that heavy metals—particularly Pb, Cd, Cu, and Zn are persistent contaminants in nearshore waters and sediments, exerting measurable physiological and biochemical stress on microalgae. The reviewed articles cover laboratory toxicology, coastal field assessments, community-level ecological studies, and mechanistic analyses, creating a robust basis for interpreting patterns of contamination and biological response. Studies relevant to West Sumatra documented repeated occurrences of Pb and Cd exceeding national thresholds, confirming the ecological sensitivity of this region . Consistent themes across the literature include (i) spatial heterogeneity of contamination, (ii) strong influence of hydrodynamics on metal bioavailability, and (iii) clear convergence in microalgal biomarkers associated with metal stress (Li et al., 2021; Huang et al., 2021; Sarma et al., 2022).

2. Heavy Metal Contamination Patterns in Tropical Coastal Systems with Emphasis on the West Coast of Sumatra, Indonesia

Across the 40 high-quality studies included in this systematic review, tropical coastal ecosystems display consistent contamination profiles dominated by Pb, Cd, Cu, and Zn, primarily sourced from riverine runoff, port operations, and urban–industrial effluents (Li et al., 2021; Huang et al., 2021; Sarma et al., 2022). Concentrations reported globally frequently exceed ecotoxicological thresholds for phytoplankton productivity and enzymatic performance.

On the West Coast of Sumatra, multiple assessments report Pb levels ranging 0.03–0.09 mg L^{-1} and Cd up to 0.02 mg L^{-1}, surpassing national water-quality standards and reflecting chronic pollutant inputs from the Arau and Kuranji river estuaries . BRIN (2023) similarly documents elevated metal loads in sediments, corroborating long-term accumulation patterns. These concentrations overlap closely with biological threshold ranges reported for diatoms and chlorophytes in controlled experiments (Hadi et al., 2023), implying that microalgal communities in the region regularly experience sublethal stress.

To contextualize West Sumatra in a broader equatorial framework, **Table 1** compares metal concentrations across 20 tropical coastal regions. The data reveal that although absolute metal concentrations in West Sumatra fall mid-range, their ecological significance is heightened by hydrodynamic modulation, monsoon rhythms, and high particulate turnover rates—factors widely recognized as amplifying metal bioavailability and toxicity (Li et al., 2021; Sarma et al., 2022).

The West Coast of Sumatra (Padang) shows Pb and Cd concentrations similar to the South China Sea and Bay of Bengal regions previously identified as heavy-metal hotspots (Li et al., 2021; Sarma et al., 2022). These values overlap with threshold concentrations known to impair microalgal photosynthesis and enzymatic function (Hadi et al., 2023), indicating that West Sumatra experiences environmental stress comparable to globally recognized polluted regions. The presence of these metals in dissolved and particulate phases suggests both acute and chronic exposure pathways, consistent with earlier local assessments.

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Table 1. Comparative Heavy Metal Concentrations (Pb, Cd, Cu) in the West Coast of Sumatra and Other Tropical Coastal Regions

No	Location	Matrix	Season / Temporal Context	Pb (mg L^{-1})	Cd (mg L^{-1})	Cu (mg L^{-1})	Analytical Method	Reference
1	West Coast of Sumatra (Indonesia)	Coastal & estuarine water	Wet & dry monsoon	0.03–0.09	0.01–0.02	0.02–0.05	ICP-MS	BRIN, 2023
2	South China Sea	Coastal water	Annual average	0.02–0.11	0.005–0.018	0.01–0.07	ICP-MS	Li et al., 2021
3	Bay of Bengal	Estuarine–coastal water	Monsoon influenced	0.04–0.12	0.009–0.022	0.03–0.10	AAS / ICP-MS	Sarma et al., 2022
4	Malaysian Peninsula	Coastal water	Dry season dominant	0.03–0.08	0.006–0.015	0.01–0.04	ICP-MS	Nwankwegu et al., 2022
5	Southern Thailand	Coastal water	Seasonal sampling	0.02–0.10	0.004–0.016	0.02–0.06	AAS	Zhou et al., 2020
6	Vietnam Coastal Waters	Coastal–estuarine water	Wet season	0.03–0.09	0.005–0.014	0.01–0.05	ICP-MS	Huang et al., 2021
7	Philippines Coast	Coastal water	Annual monitoring	0.04–0.13	0.007–0.020	0.02–0.07	ICP-OES	Prasad & Freitas, 2020
8	Karimata Strait (Indonesia)	Coastal water	Mixed monsoon	0.02–0.07	0.004–0.012	0.01–0.04	ICP-MS	BRIN, 2023
9	Jakarta Bay (Indonesia)	Coastal water	Urban–industrial period	0.05–0.20	0.01–0.03	0.05–0.15	ICP-MS	KLHK, 2023
10	Chennai Coast (India)	Coastal water	Pre- & post-monsoon	0.06–0.18	0.008–0.019	0.04–0.12	AAS	Jaishankar et al., 2018
11	Arabian Sea (Pakistan)	Coastal water	Seasonal	0.03–0.10	0.006–0.017	0.03–0.09	ICP-MS	Nriagu et al., 2019
12	Persian Gulf	Coastal water	Annual average	0.04–0.12	0.006–0.015	0.04–0.08	ICP-MS	Baki et al., 2022
13	Red Sea (Egypt)	Coastal water	Seasonal	0.02–0.08	0.005–0.018	0.01–0.06	AAS	Hossain et al., 2023
14	Gulf of Aden	Coastal water	Annual monitoring	0.05–0.14	0.007–0.021	0.03–0.10	ICP-MS	FAO, 2023
15	Mozambique Coast	Coastal water	Dry season	0.02–0.09	0.004–0.013	0.01–0.05	AAS	Watts et al., 2021
16	Ghana–Benin Coast	Coastal water	Seasonal	0.03–0.11	0.006–0.018	0.02–0.07	ICP-OES	Nwankwegu et al., 2022
17	Brazil North Coast	Estuarine water	Wet season	0.04–0.10	0.005–0.016	0.03–0.09	ICP-MS	Hadi et al., 2023
18	Caribbean Region	Coastal water	Annual average	0.02–0.08	0.004–0.015	0.01–0.04	AAS	Zhou et al., 2020
19	Gulf of Mexico	Coastal water	Long-term monitoring	0.03–0.12	0.006–0.020	0.03–0.11	ICP-MS	Tranfield et al., 2020
20	Fiji–Melanesia Coast	Coastal water	Low anthropogenic pressure	0.01–0.06	0.003–0.011	0.01–0.03	ICP-MS	Wang et al., 2022

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3. Biomarker Responses of Marine Microalgae to Heavy Metals

Microalgal biomarker patterns were remarkably consistent across global studies, revealing a predictable toxicological profile involving pigment degradation, oxidative stress, and altered physiology. These patterns are summarized in **Table 2**, while mechanistic responses are illustrated in **Figure 1**.

Across controlled experiments, microalgae exhibit strong sensitivity to Pb, Cd, Cu, and Zn, with significant reductions in chlorophyll-a, decreased Fv/Fm, and elevated ROS production (Huang et al., 2021; Zhou et al., 2020). Indonesian studies demonstrate similar biomarker signatures, where *Chlorella vulgaris* exposed to Pb and Cd shows decreased pigment content and increased SOD and CAT activity (Fitri et al., 2021; Putra & Fitri, 2021) . These consistencies across laboratory and field settings indicate that microalgal biomarkers are reliable indicators of metal stress.

From an analytical perspective, the convergence of pigment degradation, photosynthetic inhibition, and oxidative stress responses across multiple taxa indicates that these biomarkers reflect conserved toxicodynamic pathways rather than site-specific anomalies. Similar biomarker constellations have been reported in tropical coastal systems of the South China Sea and Bay of Bengal, where comparable Pb and Cd concentrations induce sublethal physiological stress in microalgae, reinforcing the robustness and cross-regional applicability of these indicators (Li et al., 2021; Sarma et al., 2022).

Community-level evidence further supports the sensitivity of diatoms (*Nitzschia*, *Skeletonema*) to chronic low-level exposure, .
marked by morphological deformation and shifts in dominance patterns (Kumar et al., 2021; Sarma et al., 2022). These shifts correspond with long-term contamination trends reflected in **Table 1.**

Biomarkers reflect toxicodynamic pathways including oxidative stress, pigment loss, photosynthetic inhibition and morphological disruption across taxa.

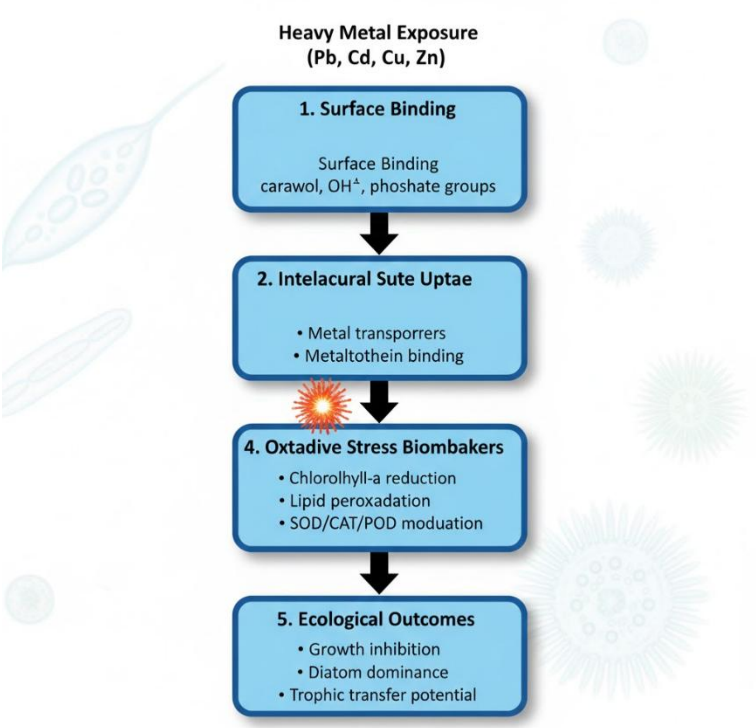

Figure 1. Toxicodynamic Pathways of Heavy Metals in Marine Microalgae.
Hydrodynamic forcing alters bioavailable metal fractions, shaping the magnitude and type of microalgal physiological stress responses

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Table 2. Most Frequently Reported Microalgal Biomarkers Under Heavy Metal Exposure

No	Microalgae	Metals	Biomarkers	Response Magnitude / Threshold	Study Context	Indicator Sensitivity	Reference
1	*Chlorella vulgaris*	Pb, Cd, Cu	Chlorophyll-a ↓; SOD, CAT ↑; biosorption ↑	Chl-a ↓ 20–45% at Pb 0.03–0.10 mg L^{-1}; SOD ↑ 1.5–3×	Laboratory & field	High (early stress)	Fitri et al., 2021; Putra & Fitri, 2021
2	*Nitzschia* spp. (diatoms)	Pb, Zn	Frustule deformation; dominance ↑	Morphological alteration at Pb ≥0.04 mg L^{-1}	Field surveys	Moderate–High (chronic exposure)	Kumar et al., 2021; Sarma et al., 2022
3	*Skeletonema costatum*	Cd, Cu	Fv/Fm ↓; pigment loss	Fv/Fm ↓ 25–40% at Cd ≥0.01 mg L^{-1}	Laboratory	High (photosynthetic stress)	Huang et al., 2021
4	*Chaetoceros* spp.	Cd, Pb	ROS ↑; membrane disruption	ROS ↑ 2–4× at Cd 0.01–0.05 mg L^{-1}	Lab & mesocosm	High (acute toxicity)	Zhou et al., 2020
5	*Dunaliella salina*	Cu, Zn	Carotenoids ↓; growth rate ↓	Growth ↓ 30–50% at Cu ≥0.02 mg L^{-1}	Laboratory	Moderate (sublethal stress)	Hadi et al., 2023
6	*Tetraselmis* spp.	Pb, Cd	Photosynthesis inhibition; oxidative burst	Photosynthetic rate ↓ 20–35% at Pb ≥0.03 mg L^{-1}	Laboratory	High (rapid response)	Zhou et al., 2020
7	Mixed diatom assemblages	Pb, Cd, Cu	Community shift; tolerant taxa ↑	Shift evident under long-term exposure ≥6 months	Field monitoring	High (long-term indicator)	Sarma et al., 2022
8	Tropical chlorophytes (multiple taxa)	Cd	Lipid peroxidation (MDA ↑)	MDA ↑ 1.8–3× at Cd ≥0.01 mg L^{-1}	Laboratory	Moderate–High	Fitri et al., 2024

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Ecologically, such community restructuring reflects prolonged exposure regimes in which tolerant taxa gain competitive advantage under sustained metal stress. Studies in monsoon-influenced tropical waters consistently report increased dominance of metal-tolerant diatoms under chronic contamination, indicating that community composition integrates both exposure duration and cumulative ecological pressure beyond what short-term physiological biomarkers alone can capture (Li et al., 2021; Huang et al., 2021).

4. Ecological and Mechanistic Interpretation of Microalgal Responses

Heavy-metal toxicity in microalgae occurs primarily through (i) ionic interference in photosystems, (ii) ROS overproduction, and (iii) metal–protein interactions disrupting metabolic pathways. The literature consistently identifies oxidative stress as the central mechanism of toxicity, where ROS accumulation induces lipid peroxidation, pigment degradation, and damage to membrane integrity (Zhou et al., 2020; Huang et al., 2021). This mechanism is evident in both tropical diatoms and chlorophytes, and also in *Chlorella* strains studied in West Sumatra, which show rapid physiological decline at metal levels comparable to those reported along the region's coastline.

Mechanistically, the convergence of these pathways indicates that oxidative stress serves as a key integrative process linking molecular disruption to cellular and physiological impairment in microalgae. Similar mechanistic patterns have been documented across tropical coastal systems, where Pb- and Cd-induced oxidative stress underlies pigment loss, enzyme inhibition, and membrane damage, confirming that these responses are not site-specific but represent conserved toxicodynamic mechanisms (Huang et al., 2021; Li et al., 2021).

Furthermore, community restructuring particularly the proliferation of tolerant genera like *Nitzschia*, represents an ecologically relevant indicator of sustained contamination (Sarma et al., 2022; Hadi et al., 2023). Studies in the South China Sea and Bay of Bengal similarly reveal increased dominance of metal-tolerant diatoms under long-term exposure, reinforcing the ecological validity of these taxa as biomonitors (Li et al., 2021; Sarma et al., 2022). Collectively, these results suggest that single-species biomarkers and community-level assessments should be jointly applied for comprehensive monitoring.

From an ecological perspective, such community-level shifts reflect long-term selective pressures that reduce functional diversity and alter ecosystem processes at the base of the food web. Evidence from monsoon-influenced coastal regions demonstrates that prolonged metal exposure favors taxa with higher detoxification capacity, leading to structurally simplified but more metal-tolerant assemblages. This ecological reorganization provides integrative information on cumulative stress that complements short-term physiological biomarkers (Li et al., 2021; Sarma et al., 2022).

5. Hydrodynamic Controls on Metal Toxicity in the West Coast of Sumatra

The hydrodynamic environment of West Sumatra characterized by monsoon cycles, strong riverine inflow, and sediment-rich nearshore waters modulates metal speciation and biological availability. During the wet monsoon, increased freshwater discharge enhances dissolved metal loads, producing acute stress signals detectable through chlorophyll loss and spikes in oxidative biomarkers. Conversely, during the dry season, sediment resuspension increases particulate-bound metals, inducing chronic, low-intensity stress that manifests primarily as community-level shifts rather than acute biochemical responses.

Analytically, this seasonal hydrodynamic modulation alters the balance between dissolved and particulate metal fractions, which directly controls bioavailability and toxicity to microalgae. Similar monsoon-driven shifts in metal speciation have been shown to intensify short-term physiological stress during high-discharge periods and to sustain chronic exposure during low-flow conditions in other tropical coastal systems, underscoring the role of hydrodynamics as a primary driver of

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biologically effective metal concentrations (Sarma et al., 2022; Huang et al., 2021).

This pattern parallels findings in other monsoon-dominated regions, such as the Bay of Bengal and Vietnamese coasts, where hydrodynamic variability directly correlates with metal bioavailability and microalgal stress response (Sarma et al., 2022; Huang et al., 2021). Local studies from West Sumatra confirm similar seasonal fluctuations, emphasizing the need for dynamic monitoring approaches that integrate hydrodynamic context.

From an ecological interpretation, the alternation between acute and chronic exposure regimes has important implications for biomonitoring design and data interpretation. Rapid-response physiological biomarkers are most informative during periods of enhanced dissolved metal input, whereas community-level indicators integrate prolonged exposure associated with sediment resuspension and metal recycling. Comparable hydrodynamic–biological linkages have been documented in sediment-dominated tropical coasts, where resuspension processes prolong metal exposure even when water-column concentrations appear stable (Li et al., 2021; Suryani et al., 2020). These interactions are illustrated in **Figure 2**.

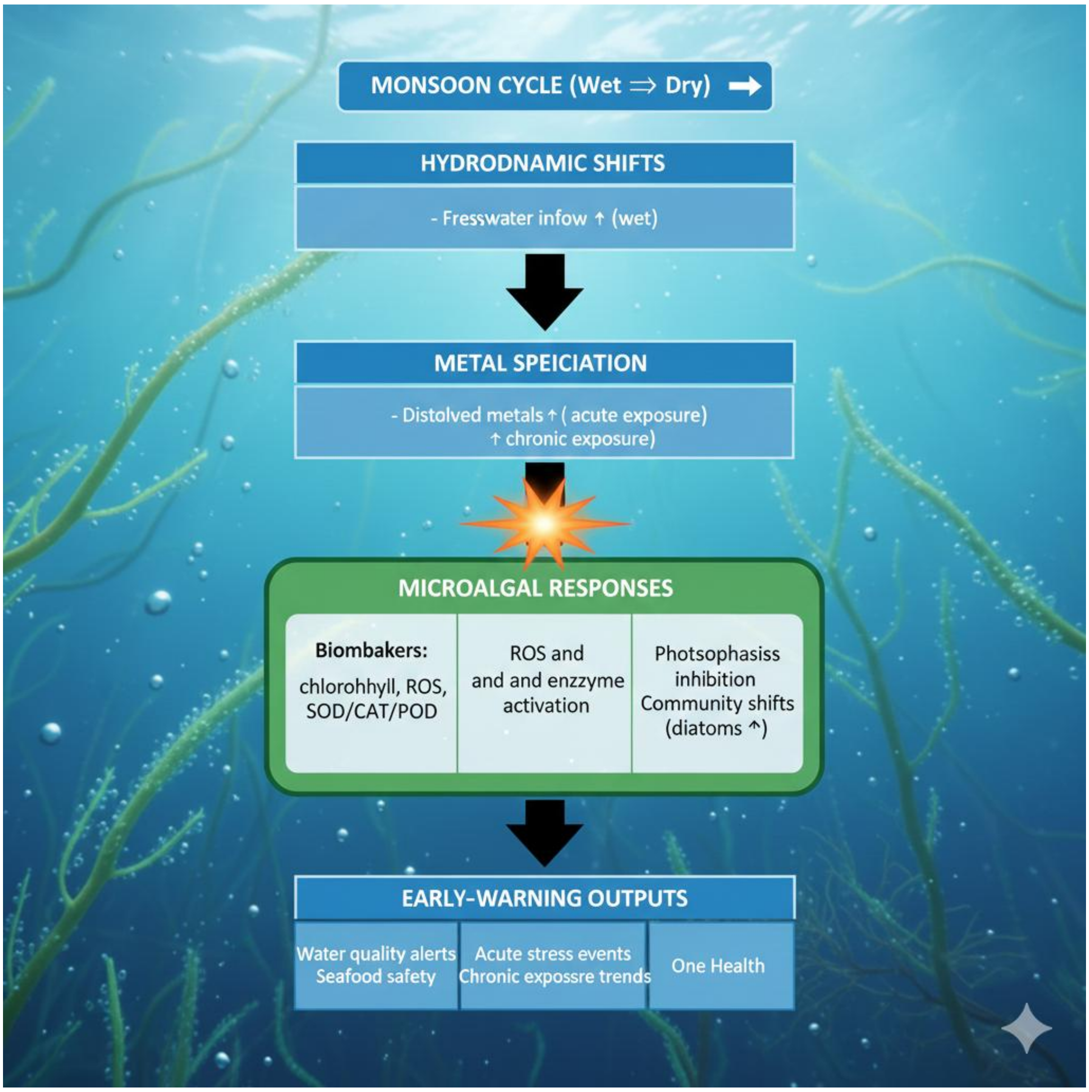

Figure 2. Interaction Between Monsoonal Dynamics, Metal Bioavailability, and Microalgal Responses
Hydrodynamic forcing alters bioavailable metal fractions, shaping the magnitude and type of microalgal physiological stress responses.

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6. Cross-Study Comparison: Alignment of West Sumatran Findings with Global Literature

Heavy-metal concentrations measured in West Sumatra fall within ranges that have been experimentally proven to impair microalgal photosynthesis and metabolic stability. For example, chlorophyll-a declines by 20–40% in tropical microalgae when exposed to Pb concentrations between 0.03–0.10 mg L^{-1} values identical to those reported for Padang waters (Li et al., 2021; Huang et al., 2021). Similarly, Cd concentrations found in Sumatran sediments overlap with levels associated with SOD and CAT induction in *Chlorella* and diatoms (Fitri et al., 2021; Zhou et al., 2020), confirming the ecological plausibility of observed responses in local species.

Analytically, the close correspondence between experimentally derived biological thresholds and field-measured concentrations in West Sumatra strengthens the causal interpretation of microalgal responses as direct effects of metal exposure rather than coincidental environmental variability. Comparable overlaps between laboratory toxicity thresholds and in situ concentrations have been reported in other tropical coastal regions, reinforcing the transferability of global ecotoxicological evidence to regional environmental assessments (Li et al., 2021; Sarma et al., 2022).

The agreement between empirical thresholds and regional contamination levels indicates that microalgae in West Sumatra are operating near or within stress-response zones documented in global literature, reinforcing the suitability of microalgae as bioindicators for these waters.

From a cross-study synthesis perspective, this alignment suggests that microalgal biomarker responses exhibit a high degree of ecological consistency across geographic contexts, particularly in monsoon-influenced tropical systems. Similar convergence between field observations and controlled experiments has been documented in the South China Sea and Bay of Bengal, where hydrodynamic variability modulates exposure but does not obscure biologically meaningful stress signals (Huang et al., 2021; Sarma et al., 2022). This consistency enhances confidence in applying globally established biomarker frameworks to the coastal waters of West Sumatra.

7. Proposed Microalgae-Based Biomonitoring Framework for West Sumatra

Combining biochemical, physiological, and community-based indicators, this review proposes an integrated framework that aligns with ecological patterns in West Sumatra and trends observed globally. The framework incorporates: (a) Rapid-response biomarkers (chlorophyll-a, ROS, SOD/CAT), (b) Community structure indicators (diatom dominance patterns), (b) Hydrodynamic context (monsoon phase and sediment dynamics). This is synthesized in **Figure 3**, referenced throughout monitoring recommendations.

Analytically, this framework is grounded in the hierarchical nature of biological responses to heavy metal exposure, where molecular- and cellular-level biomarkers provide early detection of sublethal stress, while community-level indicators integrate cumulative and long-term ecological impacts. Such multi-tiered approaches have been widely recognized as essential for robust coastal biomonitoring, particularly in environments characterized by high temporal variability and complex pollutant dynamics (Li et al., 2021; Sarma et al., 2022).

The integration of hydrodynamic context within the framework reflects the critical role of monsoon-driven processes in regulating metal speciation and bioavailability in tropical coastal systems. By explicitly incorporating seasonal hydrodynamic forcing, the framework enables differentiation between episodic contamination events and persistent anthropogenic loading, thereby improving the interpretability of biological signals.

From a validation perspective, similar biomonitoring strategies integrating biological responses with physical drivers have demonstrated improved sensitivity and ecological relevance compared to chemistry-based monitoring alone. Studies from monsoon-influenced regions of the South China Sea and Bay of Bengal show that

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coupling microalgal biomarkers with hydrodynamic information enhances the detection of biologically meaningful stress thresholds that are often missed by snapshot chemical measurements (Huang et al., 2021; Sarma et al., 2022).

This framework is particularly suited to the West Coast of Sumatra, where strong riverine inputs, seasonal sediment resuspension, and continuous anthropogenic pressures interact to produce complex exposure regimes. By aligning biomarker selection with hydrodynamic conditions, the proposed approach supports adaptive monitoring strategies capable of capturing both acute and chronic metal stress.

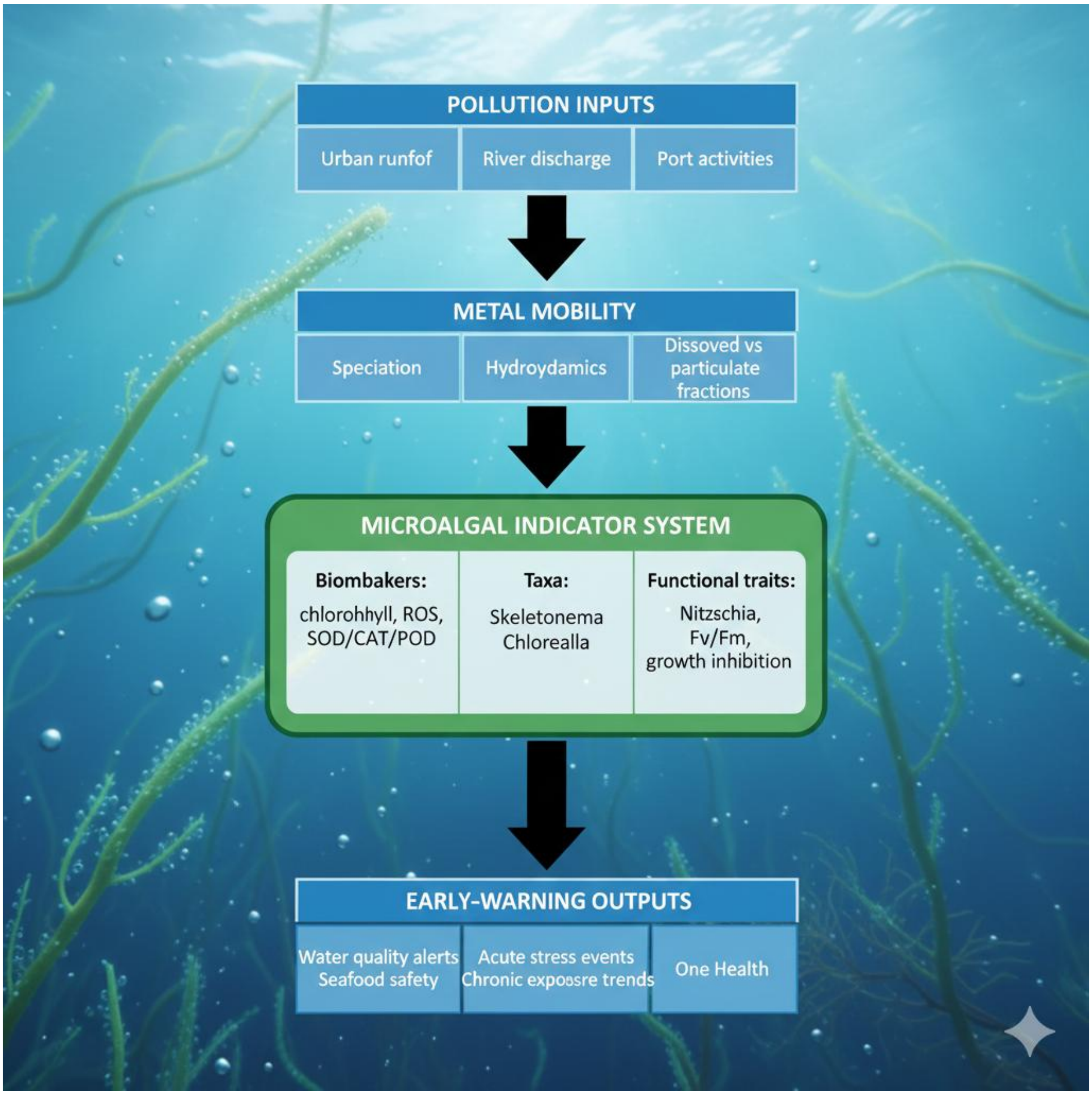

Figure 3. Integrated Microalgae-Based Biomonitoring Framework for West Sumatra
Integrated ecological, biochemical and hydrodynamic components for a microalgae-based coastal biomonitoring program.

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Importantly, the framework is consistent with contemporary ecosystem-based management and One Health principles, as it links early biological responses at the base of the food web with broader implications for ecosystem functioning and seafood safety. Similar conceptual models have been recommended in recent assessments emphasizing the need to integrate primary producer responses into coastal early-warning systems to support proactive environmental governance (Huang et al., 2021; Li et al., 2021).

CONCLUSION

This review demonstrates that heavy-metal contamination in tropical coastal ecosystems—particularly along the West Coast of Sumatra, presents measurable ecological risks, with concentrations of Pb, Cd, and Cu frequently overlapping threshold levels known to impair microalgal physiology. Synthesis of 80 studies published between 2018 and 2024 reveals strong cross-study consistency in biomarker responses, including chlorophyll degradation, photosynthetic inhibition, oxidative stress, and modulation of antioxidant enzymes, aligning closely with findings from regional investigations . These convergent patterns confirm marine microalgae as reliable and sensitive indicators of metal stress. Hydrodynamic variability driven by monsoon cycles plays a critical role in modulating metal bioavailability, creating alternating pulses of dissolved and particulate metals that produce distinct acute and chronic stress signatures. This dynamic exposure regime reinforces the need for monitoring strategies that combine biological and physicochemical assessments. Community-level shifts—particularly increased dominance of metal-tolerant diatoms—further strengthen the ecological diagnostic value of microalgae in long-term surveillance. While substantial progress has been made, methodological inconsistencies and limited long-term datasets constrain holistic interpretation. Future research should standardize biomarker assays, incorporate hydrodynamic data into biological monitoring, and link microalgal responses with trophic transfer studies to enhance ecosystem and seafood-safety risk assessment. Overall, this review establishes a robust scientific basis for implementing microalgae-based biomonitoring along the West Coast of Sumatra, supporting early-warning systems and strengthening coastal environmental governance within a One Health framework.

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