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An integrated multi-barrier strategy to mitigate heavy metal contamination in coastal aquaculture for sustainable development

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ABSTRACT

Heavy metal contamination in coastal aquaculture threatens marine ecosystems and food security (SDG 14, SDG 3). This study evaluates whether integrating nature-based solutions and culturally rooted local wisdom effectively mitigates cadmium (Cd) and lead (Pb) contamination in shrimp and mud crabs from East Lampung, Indonesia. Using a mixed-method field and laboratory design, contamination is traced from ponds to consumable products. Results indicate that mangrove-adjacent ponds have significantly lower metal loads, serving as critical ecological buffers. Furthermore, traditional post-harvest spice-based culinary processing (*woku*) synergistically eliminated 80.5% of Cd and 92.1% of Pb bioaccumulation while preserving essential macronutrients. Cultivation-level probiotic treatments also rehabilitated degraded water quality. It is concluded that combining ecological mangrove buffers, clean aquaculture technology, and indigenous post-harvest practices (*Halalan Thayyiban*) provides a socio-economically viable, multi-barrier strategy to enhance environmental resilience and food safety in polluted coastal communities.

Keywords: coastal aquaculture, environmental toxicology, local wisdom, marine pollution, sustainable development

INTRODUCTION

The rapid expansion of coastal aquaculture in the Asia-Pacific region has had a significant impact on its role in providing global food security, supporting rural livelihoods, and driving regional economic development. In recent decades, there has been a transition from conventional fishing to intensive aquaculture, which has resulted in the transformation of tropical estuarine landscapes into significant economic hubs. These areas are primarily utilised for the intensive cultivation of highly valued export commodities, including vannamei shrimp (*Litopenaeus vannamei*) and mud crabs (*Scylla serrata*). Nevertheless, this accelerated socio-economic growth has come at the cost of significant ecological repercussions. These critical coastal aquaculture systems are increasingly exposed to profound environmental contamination, a degradation primarily driven by upstream land-use intensification, rapid urban industrialisation, unregulated domestic waste disposal, and the massive discharge of agricultural runoff laden with complex agrochemicals. Among the most persistent, ubiquitous, and problematic contaminants in these dynamic aquatic systems are cadmium (Cd) and lead (Pb) (Kadaverugu et al., 2022; Newton et al., 2020).

Cadmium and lead are two non-essential, highly toxic heavy metals that pose an unprecedented risk to environmental sustainability and public health. In contrast to organic pollutants, the inherent stability of heavy metals renders them resistant to biological or chemical degradation in natural environments. Instead, these contaminants have a propensity to accumulate in estuarine sediments, where they undergo continuous circulation at the intricate interface between water and sediment, driven by the rhythmic fluctuations of tides and hydrological processes. This dynamic interaction ultimately results in the entry of heavy metals into aquatic food webs through a variety of biological pathways (Tang et al., 2022). Downstream aquaculture environments are disproportionately vulnerable to this phenomenon, as estuarine channels and coastal rivers act as primary hydrological conduits, actively transporting massive pollutant loads from expansive upstream catchments directly into enclosed coastal ponds, lagoons, and nearshore farming areas. Within these confined aquaculture systems, the underlying sediments act as a double-edged sword: they function simultaneously as a primary sink that traps the heavy metals and a secondary source of contamination that gradually releases these toxic elements back into the water column during environmental disturbances, such as mechanical pond

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maintenance, extreme weather events, or shifts in salinity and redox potential (Liu & Thiri, 2021).

Shrimp and mud crabs, as fundamentally benthic or benthopelagic crustaceans, live their entire life cycles in incredibly close physical proximity to these contaminated substrates. These organisms have been observed to consume sediment-associated organic materials, detritus, and benthic organisms, while continuously absorbing dissolved metals directly from the water column through aqueous respiration across their highly permeable gills (Kadaverugu et al., 2022; Yang, 2025). It is an irrefutable conclusion that, because of extensive research in the field of environmental toxicology, crustaceans possess a high physiological propensity to bioaccumulate heavy metals in critical internal tissues, such as the hepatopancreas, gills, and muscle fibres. While this physiological trait renders them excellent bioindicators of local ecological risk, it simultaneously renders them crucial vectors for human heavy metal exposure (Ambariyanto et al., 2023; Geng et al., 2022). It is evident that long-term exposure to low chronic doses of Cd and Pb, even over a prolonged period, has been clinically linked to severe multisystemic toxic effects in human consumers. Cadmium exposure has been linked to irreversible renal dysfunction, bone demineralization, and an increased risk of cancer (Hastuti, 2021; Thao & Cong, 2023). Lead exposure, meanwhile, is a well-documented neurotoxin that causes severe neurological deficits, cardiovascular issues, respiratory distress, and reproductive impairments (Thao & Cong, 2023).

This stark reality underscores an urgent and pressing need for holistic environmental management and mitigation strategies that are aligned directly with the United Nations Sustainable Development Goals (SDGs). It is imperative that this issue is addressed to achieve Sustainable Development Goal 14 (Life Below Water), which places significant emphasis on the prevention of marine pollution, the sustainable management of marine and coastal ecosystems, and the enhancement of coastal community resilience. Moreover, the prevention of heavy metal exposure is inherently associated with SDG 3 (Good Health and Well-being), ensuring food safety and mitigating the prevalence of non-communicable diseases associated with environmental contamination among coastal populations.

Previous environmental science research has indeed explored various interventions to mitigate heavy metal toxicity in aquatic systems. However, the vast majority of these strategies have been studied almost exclusively in isolated, fragmented disciplines. For instance, extant ecological literature focuses exclusively on nature-based solutions and ecosystem-based adaptations, extensively investigating the role of intact mangrove root systems. Mangroves are scientifically recognised for their capacity to trap fine suspended particles and immobilise toxic metals within their sulfide- and iron-rich, anaerobic rhizospheres, thereby effectively reducing metal bioavailability in the surrounding estuarine waters (Celis-Hernández et al., 2022; Lacerda et al., 2022). Another distinct research direction focuses solely on clean technology and aquaculture operational management, utilising synthetic natural absorbents (Rafiq et al., 2023) or isolated lead-tolerant remediating bacteria (Alvarado-Campo et al., 2023) to precipitate metals from the water column. Furthermore, probiotic strains are frequently studied merely as tools to enhance water quality, suppress opportunistic pathogens like *Vibrio* (Knipe et al., 2021; Ramasubburayan et al., 2025), and stabilize the pond ecology without directly linking these benefits to the reduction of human toxicological exposure (Khanjani et al., 2022, 2024). Concurrently, at the far end of the supply chain, downstream food chemistry treatments investigate natural fruit acids for their chemical chelation properties (Alristina et al., 2021; Kontominas et al., 2021), completely disconnected from the upstream ecological conditions where the food was actually grown.

Addressing this distinct interdisciplinary gap is not merely an academic exercise; it is particularly crucial for the survival and development of marginalised coastal communities. In regions such as Pasir Sakti, East Lampung, Indonesia, the implementation of advanced, highly engineered remediation technologies (such as industrial-scale reverse osmosis, ion-exchange resins, or large-scale chemical precipitation facilities) is both economically unfeasible and technologically inaccessible for traditional and semi-intensive farmers. Instead, indigenous traditional knowledge and culturally rooted practices (such as the deliberate use of specific fruit acids, the preparation of spice-rich complex dishes, and the application of herbal-fermented pond additives) may represent deeply institutionalised, community-driven environmental initiatives. These practices, which have been transmitted through generations, have a role in fostering social resilience against pervasive pollution. However, they have not yet been formally validated by the scientific literature on the subject.

It is therefore proposed that a holistic, interdisciplinary "farm-to-table" approach be pioneered to establish a direct bridge between environmental science, sustainable development, and cultural studies. The objective of this study is to thoroughly examine whether integrating upstream nature-based solutions (mangroves), clean environmental technology (probiotics), and local wisdom (traditional culinary processing) can collectively act as a unified, highly effective "multi-barrier" mitigation framework. Specifically, the study evaluates the spatial contamination variances in aquaculture ponds characterised by differing mangrove proximities, meticulously assesses the environmental rehabilitation capacity of probiotic-herbal treatments on water quality parameters and quantifies the exact decontamination efficacy of culturally rooted post-harvest processing on the reduction of Cd and Pb in edible seafood tissues. The hypothesis of this study is that the synergistic integration of ecological mangrove buffers, probiotic-driven pond management, and phytochemical-rich traditional culinary processing will significantly reduce heavy metal bioaccumulation in aquaculture products. This, in turn, will ensure food safety, preserve essential nutritional profiles, and support sustainable coastal community resilience.

MATERIALS AND METHODS

Study Area and Environmental Sampling Design

A multi-phase field observational and laboratory experimental design, incorporating numerous phases and

meticulously controlled to ensure reproducibility, was utilised to comprehensively evaluate environmental toxicology and test cascading mitigation strategies. The study was conducted in downstream coastal aquaculture systems located in Pasir Sakti, East Lampung Regency, Indonesia (approximately 5°34' S, 105°48' E). This specific region is a prominent hub for crustacean aquaculture in Sumatra, positioned at the estuary of major river systems that carry significant anthropogenic and agricultural runoff from inland urban centres and intensive farming estates, making it an ideal representative location for analysing complex tropical coastal pollution dynamics. The field sampling was conducted during the dry season to minimise the dilution effects of heavy rainfall and to capture the maximum concentration of accumulated pollutants in the stagnant pond systems.

The research area comprised actively operating brackish water ponds that were rigorously mapped and stratified based on two primary independent variables: (1) physical geographical proximity to intact, natural mangrove ecosystems (categorized as either directly 'adjacent' or 'distant' from the mangrove greenbelt), and (2) specific cultivation management typologies (categorized into traditional, semi-intensive, and intensive systems). This classification methodology strictly aligns with typological distinctions commonly established in modern sustainable aquaculture literature. In this context, pond 'intensity' reflects significant, quantifiable differences in daily water exchange management, aeration infrastructure complexity, biological stocking density, and the volume of commercial inputs utilized by the local farmers (Baldoza et al., 2020; Giri et al., 2022).

Environmental sampling was executed comprehensively across these stratified systems to capture the complete contamination cycle. The population for the environmental monitoring included the entire estuarine pond network in the Pasir Sakti sub-district, from which a representative sample of 12 distinct ponds was systematically selected. Samples of pond water, pond bottom sediment, cultured vannamei shrimp (*Litopenaeus vannamei*), and locally harvested mud crabs (*Scylla serrata*) were collected simultaneously. Water samples were taken at a depth of 50 cm using a Van Dorn water sampler, immediately filtered through 0.45 µm membrane filters, and acidified with high-purity nitric acid (HNO_3) to a pH of < 2 to prevent metal precipitation during transport. Sediment samples were collected using a standardized Ponar grab sampler. Biota samples (comprising approximately 30 adult individuals per species per pond, n = biological replicates) were harvested directly from these corresponding, pre-mapped pond systems to accurately evaluate localized, site-specific bioaccumulation factors.

Post-Harvest Mitigation Experiments

To scientifically evaluate the efficacy of the final protective barrier, highly controlled post-harvest mitigation experiments were conducted on the raw, harvested seafood tissues. This phase tested a variety of natural fruit acids (Alristina et al., 2021) alongside traditional Indonesian spice-based culinary processing methods, which are naturally rich in diverse phytochemicals (Ceramella et al., 2024; Kurek et al., 2024). Fruit acid treatments utilized naturally extracted, undiluted juices derived from locally cultivated lime (*Citrus aurantifolia*), lemon (*Citrus limon*), tamarind (*Tamarindus indica*), and pineapple (*Ananas comosus*). The fresh seafood meat was soaked in standardized volumes of these acid solutions (1:2 w/v ratio) for precisely 30 minutes at room temperature.

Following the acid treatments, the spice-based processing phase incorporated three distinct traditional Indonesian recipes, representing community-driven culinary practices with intentionally escalating levels of botanical complexity: *dabu-dabu* (Treatment A, a raw, lightly acidic condiment), *rica-rica* (Treatment B, a moderately cooked, spicy preparation), and *woku* (Treatment C, a highly complex, slow-cooked preparation). The *woku* recipe, representing the highest spice complexity, utilized a precisely measured, homogenized paste consisting of turmeric (*Curcuma longa*), garlic (*Allium sativum*), ginger (*Zingiber officinale*), lemongrass (*Cymbopogon citratus*), shallots (*Allium cepa var. aggregatum*), and noni leaf extract (*Morinda citrifolia*). The cooking process was standardized using controlled laboratory hotplates at 90°C for 25 minutes. All treated samples were strictly compared against untreated, raw seafood controls to meticulously measure the exact quantitative changes in Cd and Pb tissue concentrations, as well as to critically assess the post-processing retention of essential macro-nutrients. All laboratory cooking experiments were performed in triplicate (n = 3 experimental runs per treatment group) to ensure reproducibility.

Cultivation-Level Clean Technology Interventions

In parallel to the downstream assessments, upstream cultivation-level interventions were implemented *in situ* across selected traditional ponds through targeted probiotic-herbal supplementation (Khanjani et al., 2024; Ramasubburayan et al., 2025). This intervention was specifically designed to act as a clean technology solution to enhance overall pond water quality, foster ecological resilience, and actively suppress metal mobility. The herbal formulation utilized a complex, locally sourced botanical matrix (including noni, garlic, ginger, lemongrass, and turmeric). This botanical mixture was subsequently fermented anaerobically with a commercial multi-strain probiotic consortium (predominantly comprising *Bacillus subtilis*, *Bacillus licheniformis*, and *Lactobacillus plantarum*) for 72 hours before being applied daily to the experimental ponds at a dosage of 5 ppm.

From an economic perspective, the estimated operational cost of this probiotic-herbal treatment was calculated to evaluate field-level affordability for resource-poor farmers. Based on local market prices of raw materials, the fermentation process cost approximately IDR 250 (equivalent to USD 0.015) per kilogram of feed. This represents a highly marginal increase (<1.2%) in overall pond management expenditures.

Evaluated environmental variables for this specific intervention included critical pond water quality parameters: total ammonia nitrogen (TAN), dissolved organic carbon, heavy metal concentrations (Cd, Pb), the abundance of opportunistic pathogenic *Vibrio* spp., and quantitative ecological cell counts of natural phytoplankton and zooplankton populations. To assess the direct biological impact of this environmental management on the cultured species, shrimp performance variables encompassed physical

growth metrics (average body length and final body weight) and comprehensive nutritional tissue composition profiling (total protein percentage, crude fat percentage, and calcium content).

Laboratory Analytical Procedures

Analytical determinations for Cd and Pb concentrations across all diverse matrices were executed using rigorous, globally accepted standard laboratory procedures for trace metal analysis (American Public Health Association [APHA], 2017). Prior to instrumental analysis, homogenised biota tissues and dried, sieved sediment samples underwent standardised, aggressive wet acid digestion processes using a specific mixture of concentrated, analytical-grade nitric acid (HNO_3) and perchloric acid ($HClO_4$). Post-digestion, the dissolved heavy metal concentrations were precisely quantified using an Atomic Absorption Spectrophotometer (AAS).

Instrument calibration curves were constructed using a series of multi-element standard solutions at concentrations of 0.00, 0.01, 0.05, 0.10, 0.25, and 0.50 $mg.L^{-1}$. The instrumental response demonstrated excellent linearity across the working concentration range. For Lead (Pb), the linear calibration equation was established as $y = 0.7409x + 0.00196$, where y represents the instrumental absorbance and x represents the analyte concentration in $mg.L^{-1}$; the curve exhibited a slope (b) of 0.74094, a y-intercept (a) of 0.00196, and a correlation coefficient (r) of 0.9961. For Cadmium (Cd), the linear calibration equation was determined as $y = 1.02241x + 0.00127$, exhibiting a slope (b) of 1.02241, a y-intercept (a) of 0.00127, and an excellent correlation coefficient (r) of 0.9983, confirming high instrumental precision.

The analytical method was validated in terms of sensitivity and accuracy. The limit of detection (LOD) and limit of quantification (LOQ) for Pb were 0.001 $mg.kg^{-1}$ and 0.003 $mg.kg^{-1}$, respectively. For Cd, the LOD was 0.001 $mg.kg^{-1}$ and the LOQ was 0.003 $mg.kg^{-1}$. The instrumental precision was evaluated by triplicate analysis of samples, showing relative standard deviations (RSD) below 5.0%. The accuracy of the digestion and analytical procedures was verified by spike recovery tests, which yielded satisfactory recovery rates ranging from 95.8% to 98.4% for both elements.

Nutritional profiling of the consumable seafood tissues was conducted following the rigorous methodologies established by the Association of Official Analytical Chemists (AOAC International, 2019). Rigorous microbiological plating on selective Thiosulfate-Citrate-Bile Salts-Sucrose (TCBS) agar was used specifically for the precise isolation and quantitative abundance counting of *Vibrio* bacterial colonies (Vaiyapuri et al., 2021).

Statistical Analysis

All raw quantitative data collected from the field observations, water quality testing, and nutritional profiling were subjected to rigorous statistical evaluation using the Statistical Package for the Social Sciences (SPSS) software, version 22. To determine the statistical significance of the differences between the various intervention and control groups, Kruskal-Wallis non-parametric tests (for non-normally distributed environmental data) and one-way Analysis of Variance (ANOVA) (for normally distributed nutritional data) were employed, with the threshold for statistical significance strictly set at $p < 0.05$. Furthermore, to evaluate the actual magnitude and practical significance of the applied interventions, Cohen's d Effect Size tests were calculated for targeted pairwise comparisons. Effect sizes were categorized according to standard psychological benchmarks, ranging from *Ignored* (<0.2) up to *Very Large* (>1.2) effects (Cohen, 1988). Advanced data visualization was specifically programmed and generated using R software (R Core Team, 2023) utilizing the robust *ggplot2* package (Wickham, 2016).

RESULTS AND DISCUSSIONS

Ecological Resilience: Spatial Distribution and Bioaccumulation

The extensive field measurements across the Pasir Sakti study area revealed exceptionally distinct, highly significant spatial and system-based patterns governing the distribution of heavy metal contamination. Ponds located at a geographical distance far from intact mangrove ecosystems consistently exhibited significantly higher concentrations of both Cd and Pb in their benthic sediments and within the active water column compared to aquaculture ponds situated directly adjacent to dense mangrove greenbelts (**Figure 1** and **Figure 2**). Furthermore, the data indicated that traditional, largely unengineered ponds generally contained higher, more volatile contaminant loads than their semi-intensive and intensive counterparts.

These robust spatial findings align seamlessly with the broader ecological and environmental science consensus that healthy, dense mangrove ecosystems serve as highly effective, nature-based solutions and incredibly potent natural heavy metal sinks within vulnerable estuarine environments (Awuku-Sowah et al., 2022; Bhowmik et al., 2022). The significantly lower contamination levels observed in ponds physically adjacent to mangroves empirically confirm their critical, irreplaceable function in protecting coastal biodiversity hotspots and actively limiting contaminant mobility (Hastuti, 2021). From a biogeochemical standpoint, the complex, highly interwoven mangrove rhizosphere, which is typically profoundly anaerobic and exceptionally rich in natural organic matter, actively facilitates the proliferation of sulfate-reducing bacteria. This specific microbiological activity leads directly to the widespread precipitation of highly insoluble, stable metal sulfides within the soil matrix, thereby permanently trapping and immobilizing free Cd and Pb ions before they can infiltrate the adjacent aquaculture water supplies (Tang et al., 2022).

Conversely, the significantly elevated, often hazardous heavy metal loads observed in ponds situated far from mangroves heavily underscore the severe ecological and socio-economic risks associated with unfettered hydrological openness and the total absence of these critical ecological interception structures (Celis-Hernández et al., 2022; Lacerda et al., 2022). Furthermore, the highly significant, aggressive bioaccumulation definitively observed in the harvested biota emphasises a critical, non-negotiable rule for modern coastal

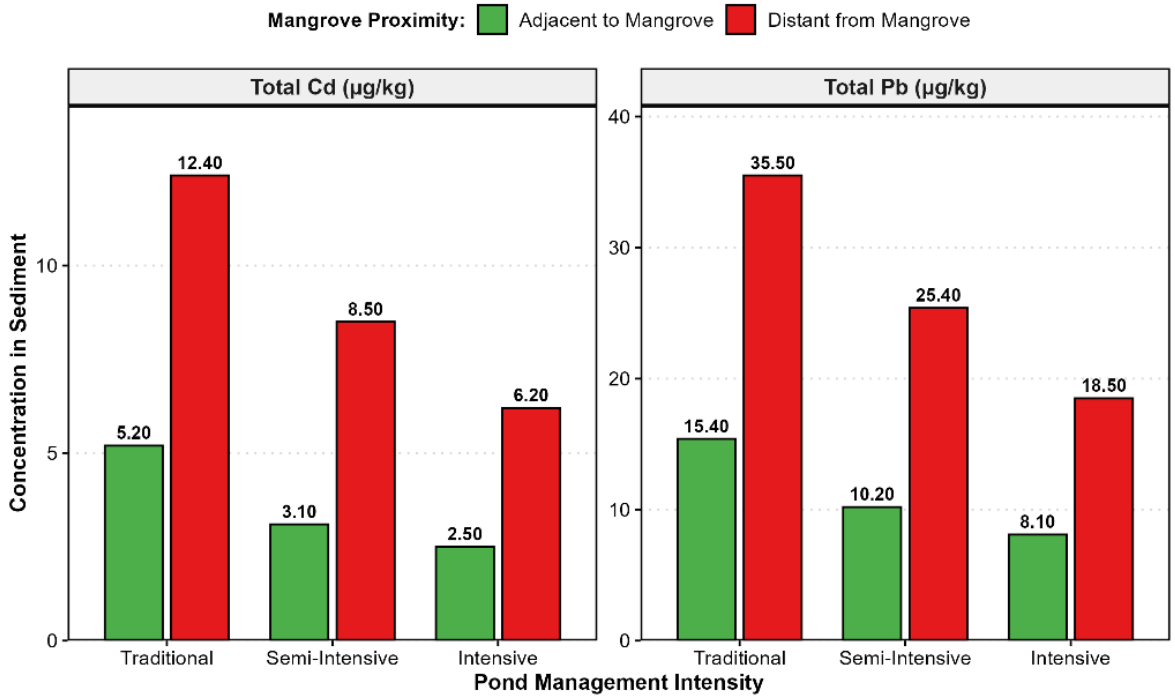


Figure 1. Spatial distribution of heavy metal (cadmium and lead) concentrations in pond sediments across different mangrove proximities and management intensities (Source: Authors' own elaboration)

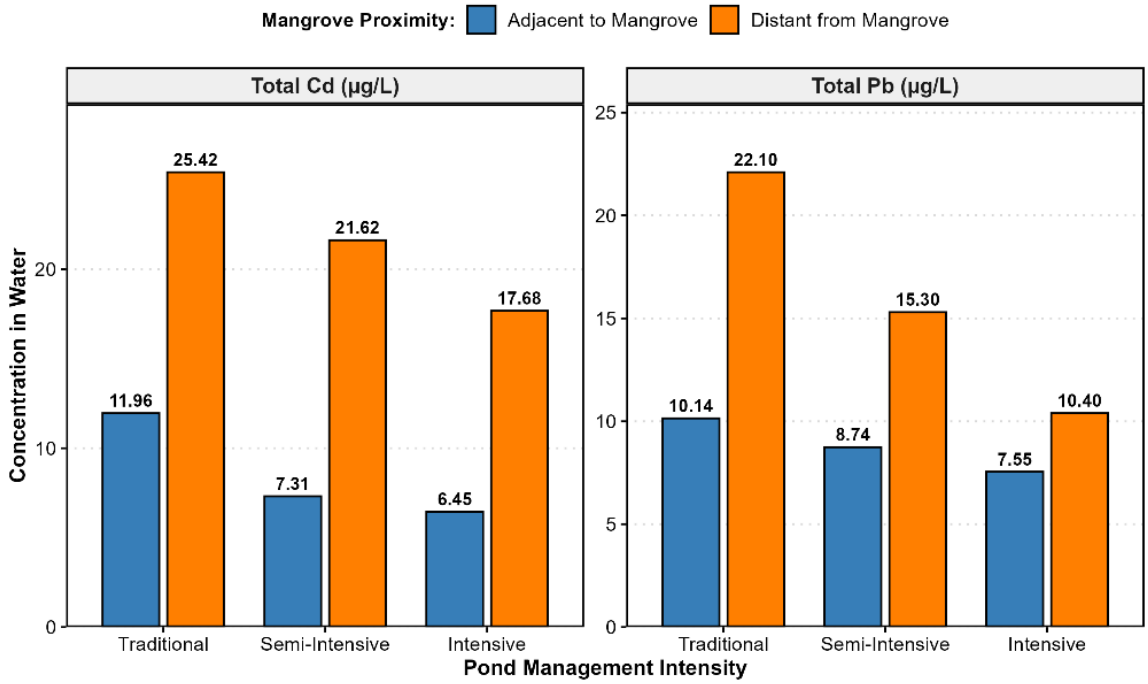


Figure 2. Heavy metal (cadmium and lead) concentrations in the water column of ponds with varying mangrove proximities and management types (Source: Authors' own elaboration)

management and environmental toxicology: human health risks must be assessed through complex, species-specific exposure models and direct edible tissue testing, rather than relying solely on simplistic, highly variable basic water quality grab samples (Ambariyanto et al., 2023; Kadaverugu et al., 2022).

Post-Harvest Mitigation: The Efficacy of Cultural Practices and Local Wisdom

The results at the post-harvest, household level demonstrated that targeted treatments using accessible natural fruit acids significantly reduced heavy metal concentrations entrenched within the raw seafood tissues. Among the specific fruit variables tested, lime juice provided the absolute most potent decontamination effect, successfully

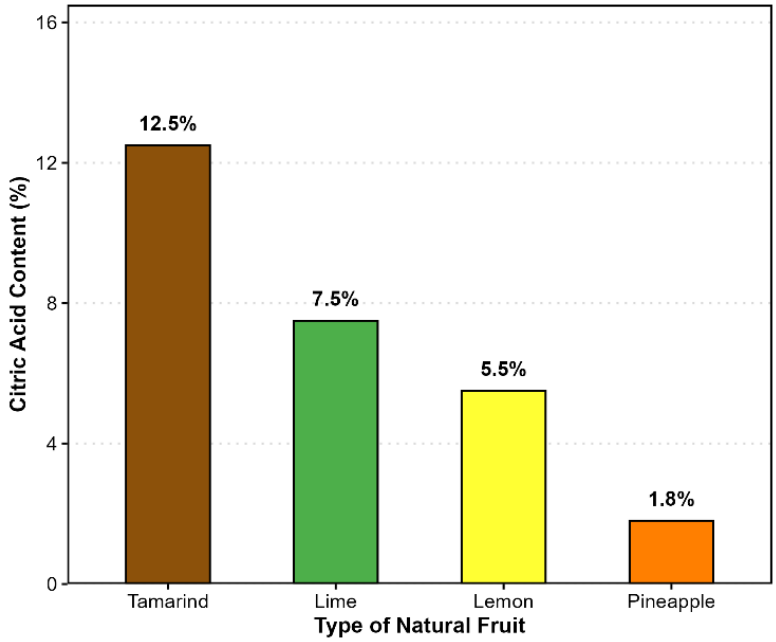


Figure 3. Relative citric acid content of various natural fruit treatments (tamarind, lime, lemon, and pineapple) (Source: Authors' own elaboration)

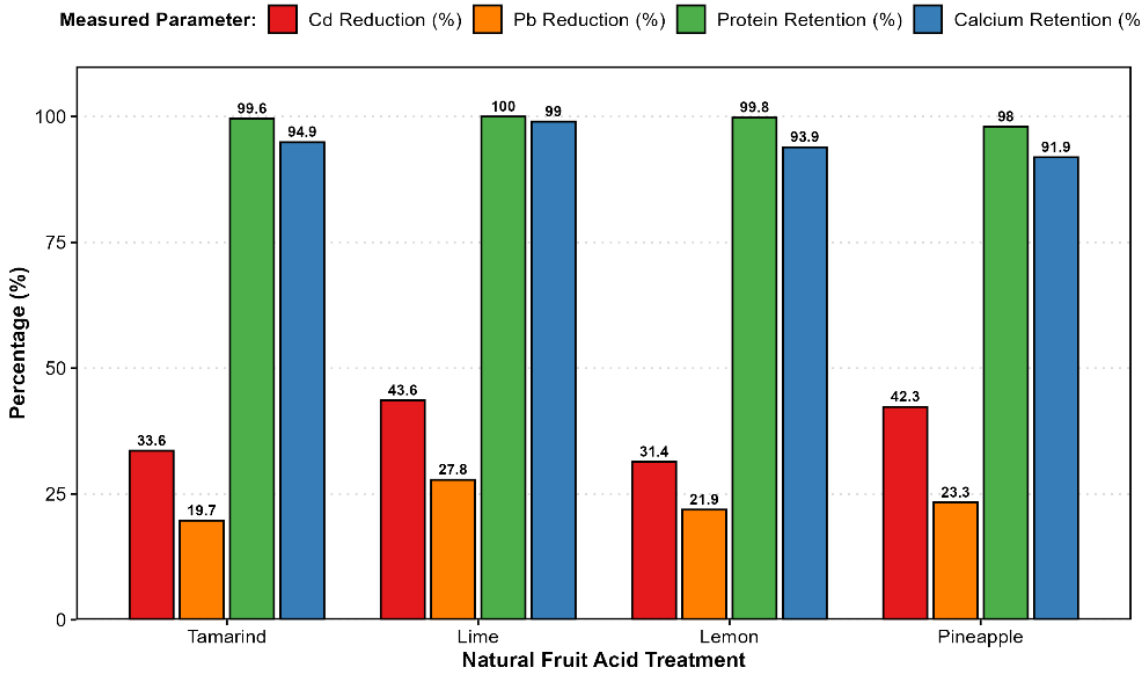


Figure 4. Efficacy of natural fruit acid treatments on the reduction of heavy metals and the retention of essential macronutrients in raw seafood tissues (Source: Authors' own elaboration)

reducing tissue concentrations of Cd by a highly significant 43.6% and Pb by 27.8% (**Figure 3** and **Figure 4**). Importantly for the context of sustainable food security, this substantial, highly beneficial reduction in toxic metals did not compromise the foundational nutritional integrity of the seafood; essential total protein and calcium levels were remarkably well-preserved post-treatment.

Reflecting post-harvest handling further along the continuum to the cooking stage, traditional spice-based processing provided a profound, synergistic decontamination effect that vastly surpassed the results of the simplistic fruit acid soaking alone. Among the culturally complex preparations tested, *woku* processing (which utilizes the highest diversity and density of local herbs and spices) achieved the absolute largest reduction. This specific indigenous cooking method reached an incredibly impressive cumulative reduction of 80.5% for Cd and 92.1% for Pb in the final, fully processed, ready-to-eat seafood (**Figure 5**).

Advanced Kruskal-Wallis hypothesis testing of the specific local spices used in this study confirmed highly significant, dynamic variations in their active organic compounds (**Table 1**). Specifically, noni leaf extract was found to be exceptionally rich in diverse flavonoids, while garlic, ginger, and turmeric were highly abundant in complex terpenoids and alkaloids.

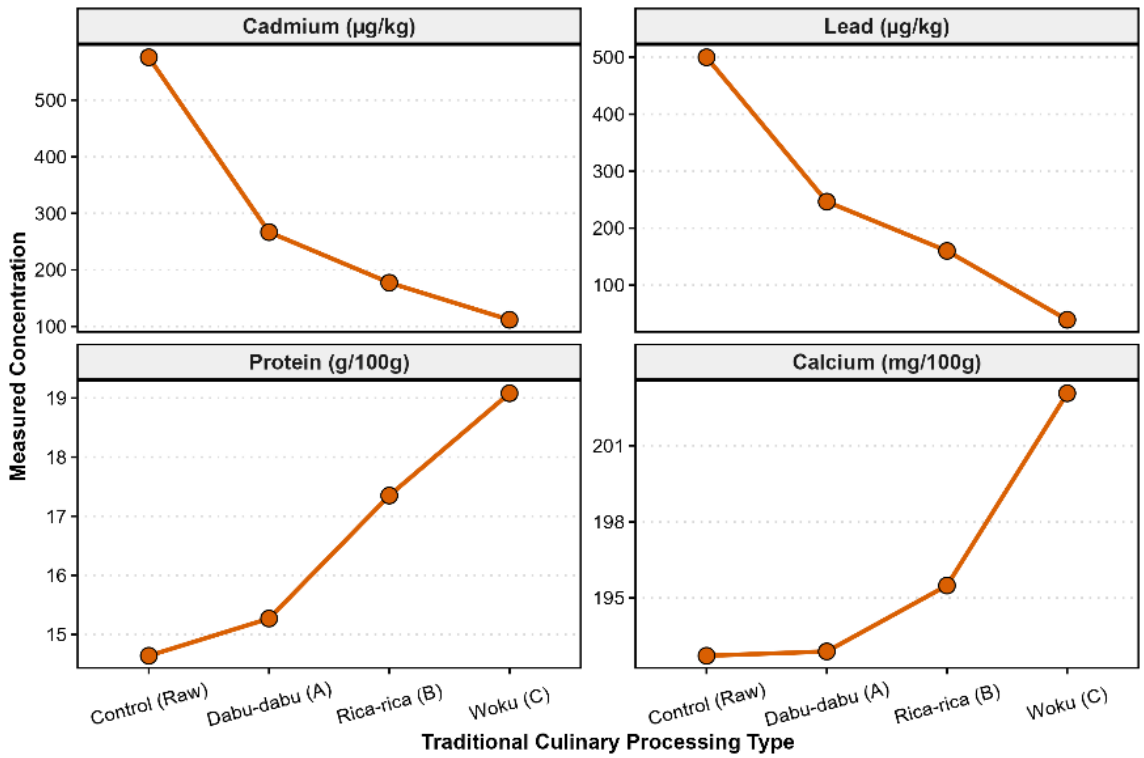


Figure 5. Synergistic effects of traditional spice-based culinary processing on heavy metal decontamination and macronutrient preservation (Source: Authors' own elaboration)

Table 1. Kruskal-Wallis test results for phytochemical variations among local spices used as food conservators

Phytochemical Compounds	Chi-Square (χ^2)	df	Asymp. Sig. (p-value)
Alkaloids	62.182	15	0.000**
Saponins	62.331	15	0.000**
Flavonoids	62.431	15	0.000**
Steroids	58.745	15	0.000**
Terpenoids	62.678	15	0.000**
Tannins	62.351	15	0.000**
Essential Oils	60.771	15	0.000**
Vitamin C	62.284	15	0.000**
Vitamin A	62.405	15	0.000**

Note: ** Significant at $p < 0.001$ level. Grouping variable: Type of natural material.

The results at the post-harvest level are practically, scientifically, and socially significant for the broader discourse on sustainable development because they successfully bridge the often-siloed fields of environmental science, chemistry, and cultural studies. They quantitatively validate that traditional, indigenous knowledge (which is frequently overlooked or dismissed as anecdotal in formal, rigid environmental policy frameworks) serves as an incredibly effective, highly rigorous, and low-cost community resilience strategy against systemic pollution. During the sustained heat of the cooking process, the physical structure of the seafood muscle tissue slightly denatures, allowing the abundant, electron-rich polyphenols and flavonoids present in local spices to penetrate the matrix. These specific phytochemical molecules feature multiple highly reactive hydroxyl and carbonyl groups that act as potent natural electron donors. It is highly hypothesized that these groups actively bind, complex, and form stable chelates with the free, highly toxic Cd^{2+} and Pb^{2+} metal cations lodged within the tissue (Ceramella et al., 2024; Dini & Laneri, 2021). Once these stable phytochemical-metal chelates are successfully formed, the liquid cooking medium (the broth or oil) facilitates the rapid physical leaching of these toxic complexes away from the edible muscle fibers and into the discarded cooking medium (Kurek et al., 2024; Parmar et al., 2024).

Environmental Management: Probiotic-Herbal Clean Technology

While post-harvest culinary treatments offer a vital final barrier, integrating mitigation strategies back at the upstream cultivation source is critical for comprehensive sustainable development. The application of the probiotic-herbal pond treatments significantly and rapidly improved multiple critical dimensions of the degraded environmental quality. Treated ponds exhibited marked, statistically significant decreases in total ambient Cd, Pb, toxic unionized ammonia, total organic carbon, and the abundance of opportunistic, highly pathogenic *Vibrio* spp. bacteria (**Figure 6**).

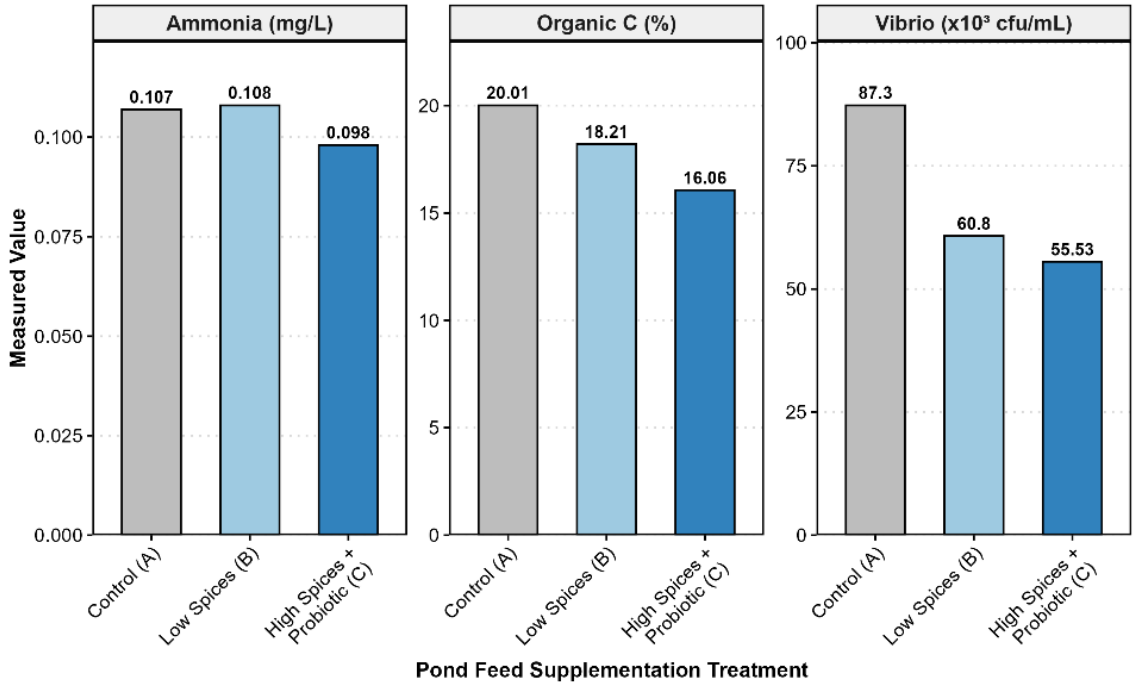


Figure 6. Impact of probiotic-herbal feed supplementation on critical pond water quality parameters (Source: Authors' own elaboration)

Table 2. Summary of data analysis on the effect of feed additive variations on pond water quality

Parameter	Test Statistic (χ^2)	Asymp. Sig.	Significant Differences	Cohen's d Effect Size
Total NH_3 (mg/L)	114.107	0.000**	C < B < A	C vs A: 2.971 (*Small*)
Organic C (%)	146.979	0.000**	C < B < A	C vs A: 2.963 (*Small*)
Total Pb (mg/L)	148.951	0.000**	C < B < A	C vs A: 5.256 (*Moderate*)
Total Cd (mg/L)	134.279	0.000**	C < B < A	C vs A: 3.476 (*Small*)
Vibrio spp. (x10^3 cfu/mL)	110.290	0.000**	C < B < A	C vs A: 2.934 (*Small*)
Phytoplankton (cells/m^3)	122.425	0.000**	C > B > A	C vs A: 3.341 (*Small*)
Zooplankton (cells/m^3)	80.832	0.000**	C > B > A	C vs A: 1.950 (*Ignored*)

Note: Pond A (Control), Pond B (Low variety spices), Pond C (High variety spices

Table 3. Summary of data analysis on the effect of feed additive variations on shrimp productivity

Parameter	Test Statistic (F)	Asymp. Sig.	Significant Differences	Cohen's d Effect Size
Protein (%)	17.217	0.000**	C > B > A	C vs A: 0.741 (*Moderate*)
Fat (%)	11.720	0.003**	C > B, A	-
Pb (mg/kg)	25.178	0.000**	C < B < A	C vs A: 0.645 (*Moderate*)
Cd (mg/kg)	15.584	0.000**	C < B < A	C vs A: 0.369 (*Small*)
Ca (mg/100g)	36.772	0.000**	C > B > A	C vs A: 1.481 (*Very Large*)
Body Length (cm)	8.809	0.012*	B > C, A	-
Body Weight (g)	8.365	0.015*	B > C, A	-

Note: * Significant at $p < 0.05$, ** Significant at $p < 0.001$.

Rigorous inferential statistical analyses confirmed that the specific supplemental herbal-probiotic feed (Treatment C, which utilized a highly varied spice profile combined with multi-strain probiotics) significantly enhanced overall water quality (**Table 2**). Furthermore, this specific intervention exerted a highly positive, cascading effect on actual biological shrimp performance (**Table 3**), actively suppressing metal bioaccumulation within the shrimp's edible tissues while simultaneously, and significantly, boosting total protein and calcium assimilation, resulting in larger, healthier harvests.

At the upstream level, this specific, highly localized pond management intervention acts as a vital, proactive, clean technology early-stage mitigation layer. The observed ecological and biochemical improvements closely align with, and significantly expand upon, existing literature regarding the application of beneficial marine microbiology in modern, sustainable aquaculture. Microbial additives, particularly lactic acid bacteria and *Bacillus* strains, actively support the critical nitrogen cycle within the pond, significantly reducing dangerous ammonia accumulation through rapid nitrification and direct cellular assimilation (Aly et al., 2020; Ringø et al., 2020). Furthermore, these robust probiotics actively stabilise complex, dynamic pond microbiota and aggressively outcompete pathogenic bacteria like *Vibrio* for limited nutrients and spatial colonization sites on the pond floor and within the shrimp gut, thereby drastically reducing disease

Table 4. Raw concentration values of Lead (Pb) and Cadmium (Cd) in pond water and shrimp tissues before and after multi-barrier treatments compared with international permissible limits

Matrix/ Experimental Group	Before Treatment (Phase 1)	After Treatment (Phase 2)	International Standard Limit
1. Pond Water ($mg.L^{-1}$)			
1.1. *Lead (Pb)*			
- Pond A (Control)	0.00957 ± 0.0003	0.00984 ± 0.0002	0.008 $mg.L^{-1}$
- Pond B (Low variety)	0.00754 ± 0.0002	0.00725 ± 0.0004	0.008 $mg.L^{-1}$
- Pond C (High variety)	0.00566 ± 0.0001	0.00541 ± 0.0003	0.008 $mg.L^{-1}$
1.2. *Cadmium (Cd)*			
- Pond A (Control)	0.00551 ± 0.0001	0.00576 ± 0.0002	0.001 $mg.L^{-1}$
- Pond B (Low variety)	0.00404 ± 0.0002	0.00387 ± 0.0001	0.001 $mg.L^{-1}$
- Pond C (High variety)	0.00326 ± 0.0001	0.00303 ± 0.0002	0.01 $.L^{-1}$
2. Shrimp Tissue ($mg.kg^{-1}$ ww)			
2.1 Lead (Pb)			
- Pond A (Control)	0.03503 ± 0.0012	0.02726 ± 0.0008	0.50 $mg.kg^{-1}$
- Pond B (Low variety)	0.03503 ± 0.0012*	0.02405 ± 0.0007	0.50 $mg.kg^{-1}$
- Pond C (High variety)	0.03503 ± 0.0012*	0.02346 ± 0.0005	0.50 $mg.kg^{-1}$
2.2 *Cadmium (Cd)*			
- Pond A (Control)	0.02069 ± 0.0007	0.01046 ± 0.0004	0.50 $mg.kg^{-1}$
- Pond B (Low variety)	0.02069 ± 0.0007*	0.00856 ± 0.0003	0.50 $mg.kg^{-1}$
- Pond C (High variety)	0.02069 ± 0.0007*	0.00821 ± 0.0002	0.50 $mg.kg^{-1}$

Note: Data are presented as Mean ± Standard Deviation (n = biological replicates for shrimp tissues). Phase 1 values for multi-barrier treatments are marked with (*) because they share the baseline control seafood value before processing initiation. ww = wet weight.

incidence without the need for harmful antibiotics (Knipe et al., 2021; Vaiyapuri et al., 2021).

Perhaps most crucially for environmental toxicology, the highly notable reduction in ambient heavy metals achieved via the herbal-probiotic application suggests profound bioremediation mechanisms. Probiotic bacteria produce extensive extracellular polymeric substances (EPS), which act as highly effective biological sponges. These EPS matrices, along with the specific organic exudates from the herbal components, are highly saturated with negatively charged functional groups (such as carboxyl and phosphate groups) that can actively bind, biosorb, or physically precipitate free, positively charged metal ions from the water column, permanently removing them from biological availability long before they can be absorbed across the shrimp's sensitive gills (Rafiq et al., 2023).

Analytical Validation of Trace Metal Reduction

To establish the quantitative analytical transparency of the trace metal reductions across different matrices and stages, the raw concentration values before and after treatments are systematically presented in **Table 4**.

As tabulated in **Table 4**, the raw concentrations of heavy metals in shrimp tissues prior to any specialised processing were 0.03503 $mg.kg^{-1}$ for Pb and 0.02069 $mg.kg^{-1}$ for Cd. When critically cross-examined against international regulatory safety targets established by the Food and Agriculture Organization (FAO/WHO, 1995) and European Union (European Commission, 2006), which strictly enforce a maximum permissible limit of 0.50 $mg.kg^{-1}$ for both contaminants in crustacean muscle meat, all harvested seafood fell well within the universally accepted safe zone. Following the implementation of downstream multi-barrier treatments, a significant reduction in tissue heavy metal residues was observed. The most notable treatment was the complex phytochemical-rich traditional cooking technique (*woku*). In the downstream samples, the concentrations of Pb decreased to 0.02346 mg.kg-1, and those of Pond C setups to 0.00821 mg.kg-1. This empirical reduction significantly amplifies the practical food safety margin, effectively reducing dietary health risks for coastal emerging consumers to negligible levels.

Sustainable Development and Socio-Cultural Implications

When viewed collectively and holistically, these extensive empirical findings strongly advocate for the implementation of a robust, multi-layered risk reduction model that aligns directly, tangibly, and measurably with the critical global targets of SDG 14 (marine pollution control and coastal resilience) and SDG 3 (guaranteeing food safety and reducing human toxicological exposure). By systematically and actively intercepting invisible contaminants from the raw, degraded pond environment straight down the supply chain to the consumer's dinner plate, this integrated strategy ensures comprehensive, end-to-end environmental sustainability (Alotaibi, 2023; Arshad et al., 2022).

It is important to note that the distinct interventions which have been tested and validated in this study intentionally avoid the pitfalls of technological exclusivity, patent-heavy industrial solutions and prohibitively high capital costs. Instead, they are contingent on three key factors: firstly, highly accessible local knowledge, secondly, deeply embedded indigenous culinary practices, and thirdly, highly practical, locally manageable pond microbiology. This paradigm provides empirical validation of a community-centric environmental governance framework that is rooted in culture. Within the specific socio-cultural context of Indonesian paradigms and broader Southeast Asian coastal communities, this approach is in direct and profound alignment with the deep-seated ethical teachings of "Halalan Thayyiban". This fundamental concept demands that food be not only legally permissible (*Halal*) but also inherently wholesome, safe, pure, highly nutritious, and produced

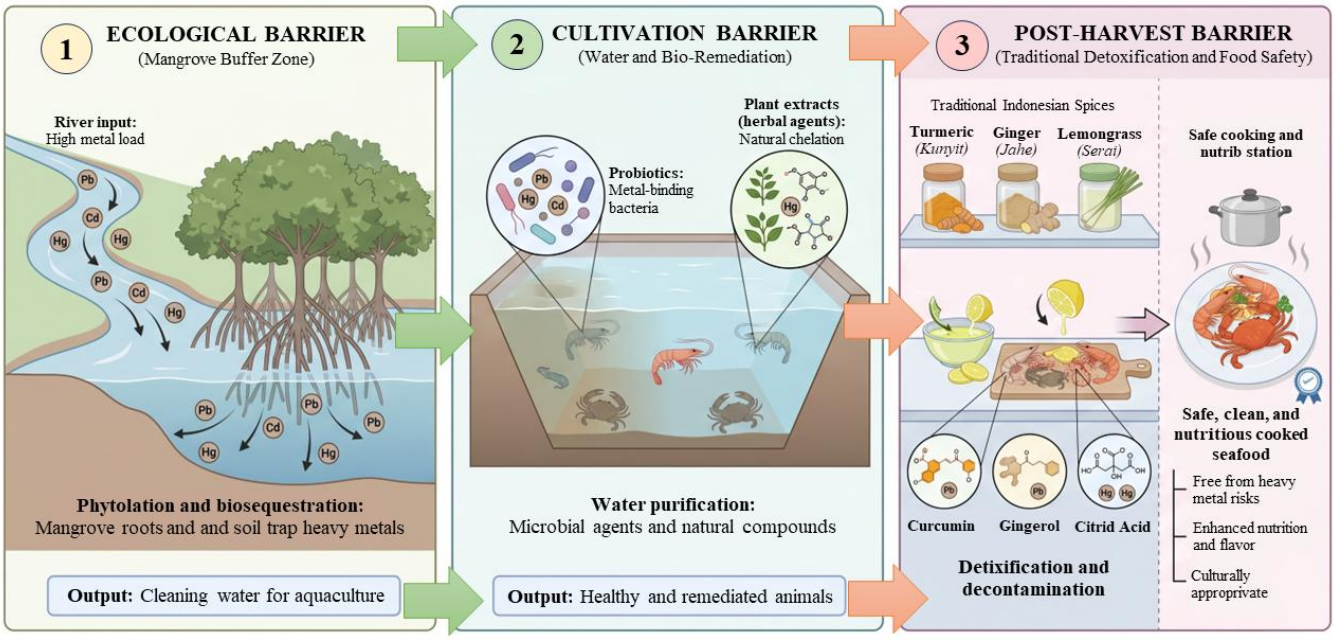


Figure 7. Conceptual framework of the integrated coastal management mitigation strategy, illustrating the sequential interception of heavy metal contamination from the ecosystem to the post-harvest processing level (Source: Authors' own elaboration)

without causing harm to the environment (Ahmad & Nordin, 2023; Arifin et al., 2021).

The combination of simple, accessible acid soaking, complex traditional spice chelation, and straightforward probiotic environmental management represents a novel approach to the restoration of aquaculture products. In this study, the efficacy of this method in restoring highly contaminated, low-quality aquaculture products to a state of high toxicological safety and superior nutritional value is demonstrated. This finding indicates that local cultural values and indigenous socio-agricultural practices are conducive to the development of highly inclusive, inherently sustainable societies. Consequently, it is imperative that these practices be formally integrated into regional environmental resilience frameworks, rather than being marginalised by purely technocratic policies (Mokti et al., 2024). The comprehensive integration and scientific validation of this mitigation pathway is visually summarised in **Figure 7**.

CONCLUSIONS

This study decisively demonstrates that severe, systemic heavy metal contamination within vulnerable coastal aquaculture systems can be highly effectively mitigated through a holistically integrated, multi-barrier strategy that successfully bridges complex environmental science, marine microbiology, and sustainable development paradigms. The data unequivocally show that Cd and Pb concentrations were significantly lower in aquaculture ponds situated directly adjacent to intact mangroves, powerfully underscoring the vital, irreplaceable function of nature-based solutions as primary ecological buffers against upstream pollution. Furthermore, the aggressive bioaccumulation observed in both shrimp and mud crabs strongly emphasises that comprehensive environmental risk assessments, to truly protect human health, must require complex, species-specific tissue modelling rather than relying solely on simplistic, highly variable basic water quality grab samples (Ambariyanto et al., 2023; Kadaverugu et al., 2022).

Crucially, downstream post-harvest treatments utilizing locally sourced, highly accessible natural fruit acids and deeply indigenous complex spices provided profound, synergistic reductions in toxicity (eliminating over 80% of Cd and 90% of Pb) while successfully preserving essential macronutrient integrity. Coupled directly with upstream cultivation-level probiotic clean technology that actively rehabilitates degraded, toxic pond water via biological biosorption and competitive exclusion, this holistic approach successfully transforms culturally rooted local knowledge into a scientifically validated, highly replicable blueprint. Ultimately, this community-driven strategy provides a highly economic, socio-economically viable, and low-cost multi-barrier framework for securing the toxicological safety and long-term sustainability of aquaculture food systems, directly supporting the critical global mandates of SDG 14 and SDG 3 within increasingly polluted coastal communities.

To translate these empirical findings into active environmental governance, specific policy recommendations are directed toward the Indonesian government (particularly the Ministry of Marine Affairs and Fisheries and the National Agency of Drug and Food Control - BPOM) and the regional aquaculture industry:

1. Formal integration of mangrove conservation zones as mandatory ecological buffers adjacent to coastal brackish water ponds, creating physical barriers that intercept heavy metals from inland agricultural runoff.
2. Promoting national standardisation and subsidy frameworks for low-cost, eco-friendly probiotic-herbal

pond additives, providing an affordable alternative to hazardous chemical agents.

3. Incorporating culturally rooted kearifan lokal (such as natural acid wash and traditional botanical processing) into household food safety campaigns, raising awareness of low-cost detoxification barriers for polluted seafood in developing coastal communities.

However, acknowledging the complexities of biological and chemical systems, there are some important, distinct limitations of this applied research that must be recognized. Natural herbs, traditional culinary spices, and fresh fruit acids can vary significantly in their precise phytochemical composition depending heavily on their specific botanical source, exact ripeness at harvest, highly localized soil conditions, and subsequent post-harvest storage methods, which may consequently cause slight, unpredictable variations in their ultimate chemical chelation efficacy. Furthermore, highly aggressive, intense phytochemical chelation processes carry the theoretical, unintended potential to inadvertently bind and simultaneously strip essential trace minerals from the complex food matrix during cooking. While solid-state binding tests (such as FTIR or SEM-EDS) were not performed in this study due to equipment accessibility constraints in the regional field, the dramatic drop in analytical tissue residues indirectly validates the extraction pathway. Therefore, critical potential future research regarding this vital issue should prioritize involving highly controlled, advanced metabolomic profiling, FTIR/SEM-EDS solid-state binding analysis, and precise elemental tracking. Such future studies are necessary to fully, comprehensively map the specific molecular chelation pathways of spices and to rule out any negative nutritional trade-offs across a wider variety of aquatic and metalloid species (such as Mercury or Arsenic).

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AI statement: The authors stated that no generative AI tools were used during the study for data generation or content creation.

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Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

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