



Heavy Metal Determination in Seaweed (*Caulerpa lentillifera*) Sold in Selected Sampaloc Market, Manila: Basis for Bioremediation

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Abstract

Heavy-metal contamination in edible marine resources represents an environmental and public-health concern because persistent metals may accumulate in aquatic organisms and subsequently enter the human food chain. This study determined the concentrations of arsenic (As), lead (Pb), cadmium (Cd), and mercury (Hg) in *Caulerpa lentillifera*, locally known as sea grapes or lato, sold in selected markets in Sampaloc, Manila. Seaweed samples with declared geographic origins from Batangas, Cebu, and Marinduque were prepared through washing, lyophilization, grinding, acid digestion, filtration, and dilution. Heavy-metal concentrations were analyzed using Atomic Absorption Spectrophotometry and Inductively Coupled Plasma Spectrometry. Results showed that arsenic concentrations were below 0.3 ppm, lead below 0.3 ppm, cadmium below 0.1 ppm, and mercury below 0.03 ppm in all analyzed samples. These values were below the international maximum limits used as comparative benchmarks in the study. The findings indicate that the tested seaweed samples presented low detectable levels of the four heavy metals examined and suggest minimal contamination-related risk within the analytical limits of the methods employed. The results also provide baseline information for continued monitoring of edible seaweeds and for further investigation of the capacity of *C. lentillifera* to accumulate metals and potentially contribute to bioremediation applications. Continued surveillance and the development of locally applicable standards for heavy metals in edible seaweeds are recommended.

Keywords: *Caulerpa lentillifera*, heavy metals, food safety, seaweed, environmental health, bioremediation

1. Introduction

The Philippines is an archipelagic country whose extensive marine environment supports food security, livelihood, aquaculture, fisheries, and coastal economic activity. Marine resources remain particularly important to communities situated near coastal areas, where fishing and related activities contribute substantially to household income and food supply (Palomares & Pauly, 2014; Santos et al., 2011). Among these resources, seaweeds have become increasingly important because of their nutritional, ecological, and economic value. The Philippines is recognized as a major producer of commercially important seaweeds, which support both domestic consumption and the broader marine-based economy.

One edible seaweed commonly consumed in the Philippines is *Caulerpa lentillifera*, locally known as lato or sea grapes. Characterized by its small, bead-like structures, *C. lentillifera* is consumed fresh and is commonly prepared with vinegar, tomatoes, onions, and other ingredients. Studies of edible *Caulerpa* and other green seaweeds have emphasized their nutritional value, including minerals, dietary fiber, and other bioactive components relevant to human consumption (Magdugo et al., 2020; Stuthmann et al., 2023). The cultivation and harvesting of seaweed have consequently developed into an important component of marine food production and coastal economic activity in the Philippines (Estrada et al., 2021; Trono & Largo, 2019).

Despite its nutritional and economic value, the consumption of seaweed may also present environmental and food-safety concerns when marine ecosystems are exposed to potentially hazardous contaminants. Of particular concern are metals such as arsenic (As), lead (Pb), cadmium (Cd), and mercury (Hg). These substances may persist in aquatic environments and can accumulate in marine organisms. Their accumulation in edible marine organisms therefore warrants continuing attention because human exposure may occur through regular consumption (Ali & Khan, 2018; Hahn et al., 2022).

Seaweeds are particularly relevant to contaminant monitoring because of their capacity to absorb substances from the surrounding aquatic environment. Research has documented the occurrence and accumulation of heavy metals in edible seaweeds and has shown that concentrations can vary according to species, environmental conditions, location, and

exposure to anthropogenic activities (Filippini et al., 2021; Lee et al., 2022). This capacity to accumulate environmental contaminants makes seaweed relevant from two related perspectives. First, the presence of metals in edible seaweed raises questions concerning food safety and potential human exposure. Second, the ability of seaweed to absorb metals from aquatic environments provides a basis for investigating its possible application in environmental monitoring and bioremediation (Roleda & Hurd, 2019; Van Ginneken & De Vries, 2018).

Heavy-metal contamination is particularly important in highly urbanized and industrially influenced environments. Urban expansion, domestic and industrial discharges, transportation activities, agricultural runoff, and other anthropogenic processes may introduce contaminants into waterways and coastal environments. Once released, these contaminants may be transported through connected aquatic systems and eventually accumulate in sediments or marine organisms. Because seaweed is frequently consumed with minimal processing, assessment of contaminant concentrations is relevant to determining whether products reaching consumers comply with recognized safety limits.

In the Philippine context, monitoring edible seaweed is important because the commodity may be harvested from one geographic location, transported through distribution networks, and ultimately sold in urban public markets. Thus, the location where a seaweed product is purchased does not necessarily represent its geographic origin. This distinction is relevant to the present investigation because the *C. lentillifera* samples were obtained from selected markets in Sampaloc, Manila, while the seaweed products were identified as having originated from Batangas, Cebu, and Marinduque. Examining products available in the market therefore provides information about the quality of seaweed reaching consumers while also allowing consideration of different declared geographic sources.

International food-safety frameworks provide reference values against which measured concentrations of contaminants may be evaluated. However, the source study notes the absence of sufficiently specific Philippine maximum allowable limits applicable to the heavy-metal content of edible seaweeds. In this context, comparison with available international standards provides a practical basis for preliminary assessment while also highlighting the need for locally relevant monitoring and regulatory standards. Such information is important not only for protecting consumers but also for maintaining confidence in seaweed as a food product and supporting the sustainable development of the Philippine seaweed industry. This need for locally grounded, systematically integrated monitoring echoes broader calls for coordinated environmental-hazard frameworks in the Philippines, where fragmented oversight across distinct hazard types has likewise been identified as a gap warranting more integrated monitoring approaches (Atento et al., 2026).

The determination of heavy-metal concentrations in *C. lentillifera* therefore contributes to both food-safety assessment and the broader understanding of seaweed as an organism capable of interacting with contaminants in aquatic environments. Although the present study does not directly test the efficiency of *C. lentillifera* as a remediation agent, measurements of arsenic, lead, cadmium, and mercury provide baseline evidence relevant to subsequent investigations of metal accumulation and possible bioremediation applications.

Objectives of the Study

This study aimed to determine the concentrations of selected heavy metals in *Caulerpa lentillifera* sold in selected markets in Sampaloc, Manila, and to provide baseline information relevant to food safety and potential bioremediation applications. Specifically, the study sought to:

1. determine the concentrations of arsenic (As), lead (Pb), cadmium (Cd), and mercury (Hg) in *C. lentillifera* samples with declared origins from Batangas, Cebu, and Marinduque;
2. compare the measured heavy-metal concentrations with the international maximum limits used as reference standards in the study;
3. assess the implications of the detected concentrations for the safety of *C. lentillifera* intended for human consumption; and
4. provide baseline evidence that may support further investigation of the potential application of *C. lentillifera* in heavy-metal monitoring and bioremediation.

2. Review of Related Literature

2.1 *Caulerpa lentillifera* as an Edible Marine Resource

Seaweeds have become increasingly important as food resources, aquaculture commodities, and components of sustainable coastal economies. Global seaweed production has expanded considerably because of growing demand for food, industrial products, and environmentally sustainable marine resources (Chopin & Tacon, 2021; Zhang et al., 2022). In the Philippines, seaweed cultivation and harvesting are particularly significant because they provide livelihood opportunities for coastal communities while contributing to the country's marine food-production sector (Trono & Largo, 2019).

Among edible seaweeds, *Caulerpa lentillifera* is widely recognized for its distinctive appearance, nutritional characteristics, and culinary value. Often referred to as sea grapes, the species is consumed fresh in several Asian countries and has become increasingly valued as a marine vegetable. Research on *Caulerpa* and related green seaweeds has highlighted their nutritional composition, including minerals and other bioactive components relevant to food use (Magdugo et al., 2020). Structured reviews of *C. lentillifera* have likewise emphasized its cultivation, nutritional value, post-harvest management, and increasing importance for human consumption (Stuthmann et al., 2023).

Philippine research has documented the cultivation, morphology, utilization, and distribution of *Caulerpa* species. Estrada et al. (2020) examined morphological variation in *C. lentillifera* and *C. racemosa* from selected Philippine regions, while Estrada et al. (2021) described the status of sea-grape farming and wild harvesting in the country. These studies demonstrate that *C. lentillifera* is both a biologically important marine organism and an economically relevant food commodity. However, because seaweeds directly interact with surrounding seawater and sediments, their nutritional and economic value must also be considered alongside their capacity to absorb substances present in the aquatic environment.

2.2 Heavy-Metal Accumulation and Contamination in Seaweeds

Heavy metals are persistent environmental contaminants that may originate from natural processes as well as industrial activity, mining, urbanization, agricultural runoff, and other anthropogenic sources. Once introduced into aquatic environments, certain metals may accumulate in water, sediments, and marine organisms. Their persistence and potential biological effects have made heavy-metal contamination an important environmental monitoring concern (Ali & Khan, 2018).

Seaweeds are particularly relevant in this context because they can absorb and accumulate metals from surrounding aquatic environments. Van Ginneken and De Vries (2018) described seaweeds as potential biomonitoring systems for heavy-metal contamination in marine environments, while Vázquez-Arias et al. (2023) reviewed techniques for determining the cellular location of heavy metals in seaweed. These studies indicate that metal uptake and accumulation can vary according to species, environmental conditions, and physiological characteristics.

Empirical studies have documented the occurrence of metals in edible and cultivated seaweeds. Lee et al. (2022) compared heavy metals and arsenic species in seaweeds collected from different regions in Korea, while Filippini et al. (2021) investigated heavy metals and potential risks in edible seaweed products marketed in Italy. Khandaker et al. (2021) similarly examined elevated concentrations of metal(loids) in seaweed and their implications for human exposure. These studies establish that metal accumulation in seaweeds is neither uniform nor inevitably hazardous; rather, contamination varies according to environmental exposure, species characteristics, geographic conditions, and the metals examined. Determining concentrations in commercially available *C. lentillifera* therefore provides an empirical basis for evaluating whether seaweed reaching consumers contains measurable levels of contaminants of public-health concern.

Comparable Philippine biomonitoring evidence has been reported for edible aquatic vegetation: Ylagan et al. (2025) found lead, cadmium, and mercury below method detection limits in kangkong collected from three Manggahan Floodway sites, illustrating how plant tissues can support standards-based contaminant surveillance in food-producing aquatic systems. In a related coastal food-safety context, Nacino and Basit (2025) documented widespread microplastic contamination and bacterial isolates in *Decapterus macrosoma* from Cavite, demonstrating that contaminant surveillance of edible aquatic organisms increasingly encompasses multiple environmental hazards rather than metals alone.

2.3 Food Safety, Human-Health Risk, and Bioremediation Potential

The consumption of edible seaweeds presents both nutritional benefits and potential food-safety concerns. Banach et al. (2020) identified a range of hazards within the seaweed food chain, including chemical contaminants that require monitoring as production and consumption increase. Cherry et al. (2019) similarly emphasized that the health benefits associated with edible seaweed must be balanced against potential exposure to undesirable substances, including metals and excessive concentrations of certain naturally occurring elements.

Heavy metals are of particular concern because prolonged or excessive exposure may produce adverse health effects depending on the specific element, concentration, duration of exposure, and route of intake. Studies of edible seaweeds have therefore increasingly incorporated health-risk evaluation. Hahn et al. (2022), for example, assessed chemical contaminant concentrations in edible seaweeds from the Salish Sea and examined implications for consumption. Such studies illustrate the importance of interpreting measured metal concentrations in relation to recognized safety thresholds rather than assuming that the presence of a metal automatically represents a significant health hazard.

The ability of seaweeds to accumulate environmental contaminants also gives rise to another line of investigation: their potential role in biomonitoring and bioremediation. Roleda and Hurd (2019) discussed seaweed nutrient physiology in relation to aquaculture and bioremediation, while Van Ginneken and De Vries (2018) considered the use of seaweeds as biomonitoring systems for heavy-metal accumulation. These studies suggest that the same biological characteristics that

create concern when edible seaweeds accumulate contaminants may also make certain species useful for environmental monitoring or remediation. Nevertheless, identifying metals in seaweed is different from demonstrating effective bioremediation. Establishing remediation potential requires evidence concerning uptake efficiency, accumulation capacity, exposure conditions, metal removal rates, tolerance, and other physiological or environmental factors. Heavy-metal determination in edible *C. lentillifera* should therefore be treated as baseline evidence that may inform subsequent research on its remediation capacity rather than as direct proof that the species functions effectively as a bioremediation agent.

Recent Philippine work has also extended marine food-safety surveillance to microplastic contamination and Gram-negative bacterial profiles in *Sardinella fimbriata* collected from Manila Bay (Ylagan, Reyes, et al., 2026), broadening the contaminant-monitoring context surrounding edible marine resources. A related study similarly characterized microplastic contamination in household drinking-water sources in Manila, indicating that such contaminant surveillance extends beyond edible marine organisms to everyday consumer products reaching Filipino households (Ylagan, Somcio, et al., 2026). At the community-health level, Temporada et al. (2025) showed that environmental-health risk management in flood-prone Philippine communities depends not only on awareness but also on preventive attitudes, practices, and enabling conditions, underscoring the broader value of translating hazard monitoring into practical risk-reduction measures. Comparable surveillance work on zoonotic parasite exposure among dog owners in Metro Manila has similarly shown that environmental and public-health monitoring in dense urban settings depends on awareness and household practices in addition to hazard detection (Quinto et al., 2026).

2.4 Synthesis and Research Gap

The literature collectively demonstrates three important relationships relevant to the present study. First, *C. lentillifera* is an economically and nutritionally important edible seaweed whose production and consumption are significant in the Philippines and elsewhere (Estrada et al., 2021; Stuthmann et al., 2023). Second, seaweeds can absorb metals and other substances from aquatic environments, making them relevant both as potential pathways of human exposure and as biological indicators of environmental contamination (Van Ginneken & De Vries, 2018; Vázquez-Arias et al., 2023). Third, the accumulation characteristics of seaweeds have generated interest in their potential use for contaminant sequestration and bioremediation, although remediation capacity must be established through studies specifically designed to evaluate uptake and removal performance (Roleda & Hurd, 2019).

Existing studies have examined heavy-metal contamination in seaweeds across different countries and coastal environments, yet evidence concerning commercially available *C. lentillifera* reaching consumers through urban markets remains comparatively limited. Moreover, the geographic origin of seaweed may differ from its point of sale, making market-based assessment relevant to consumer exposure. The present study addresses this gap by determining arsenic, lead, cadmium, and mercury concentrations in *C. lentillifera* sold in selected Sampaloc, Manila markets and identified as originating from Batangas, Cebu, and Marinduque. By comparing measured concentrations with recognized international reference limits, the study contributes baseline evidence concerning food safety while providing an empirical starting point for subsequent investigation of the species' potential application in environmental monitoring and bioremediation.

From a sustainability perspective, Atento (2025) found that Philippine higher-education documents gave comparatively limited attention to SDG 14, highlighting the continuing need to connect local environmental vulnerabilities with systematic sustainability monitoring and education. Methodologically, experimental work on biologically active natural materials also illustrates why preliminary screening evidence should be distinguished from demonstrated functional efficacy; controlled assays are needed before broader applied claims are warranted (Laxamana et al., 2025).

3. Methodology

3.1 Research Design

The study employed a laboratory-based analytical research design to determine the concentrations of selected heavy metals in *Caulerpa lentillifera* sold in selected markets in Sampaloc, Manila. The analysis focused on arsenic (As), lead (Pb), cadmium (Cd), and mercury (Hg), with the resulting concentrations compared with the international maximum limits adopted as reference standards in the study.

3.2 Sample Sources and Collection

Samples of *Caulerpa lentillifera* were purchased from selected markets in Sampaloc, Manila. The seaweed samples were identified as having declared geographic origins from Batangas, Cebu, and Marinduque. Only seaweed samples that appeared healthy and vibrant and were free from visible signs of decay or contamination were selected. Immediately after acquisition, the samples were placed in polyethylene or polypropylene containers and stored inside a sterile ice box containing ice. Gloves were used during handling to minimize possible contamination, and quartz or borosilicate glass containers were avoided. Each sample was labeled according to its market location, date of collection, and sample number.

3.3 Sample Preparation

The collected seaweed samples were carefully washed using distilled water to remove surface impurities such as sand, salt, and microorganisms. Following washing, the samples underwent lyophilization for 25 hours to remove moisture and produce a dried material suitable for laboratory analysis. The dried seaweed was subsequently ground into a fine powder using a mortar and pestle to obtain a more homogeneous sample and facilitate subsequent digestion and analytical determination.

3.4 Acid Digestion

A measured portion of the ground seaweed sample was placed in a digestion vessel. Hydrochloric acid (HCl) served as the principal digestion acid, while a small amount of hydrogen peroxide (H₂O₂) was added to assist in the breakdown of organic material. The mixture was heated on a hot plate under atmospheric pressure until digestion was completed. The digested solution was then allowed to cool to room temperature and was filtered using filter paper to remove residual undissolved material. The resulting filtrate was subsequently diluted with deionized water prior to instrumental analysis.

3.5 Heavy-Metal Determination

The concentrations of arsenic, lead, cadmium, and mercury were determined using Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled Plasma Spectrometry (ICPS), as specified in the source study. The laboratory analysis generated concentration values expressed in parts per million (ppm). Arsenic and mercury were determined using Atomic Absorption Spectrophotometry, while lead and cadmium were determined using Inductively Coupled Plasma Spectrometry.

3.6 Data Analysis and Interpretation

The measured concentrations of the four target metals were summarized according to the declared geographic origin of the seaweed samples. Results were reported in parts per million and compared with the maximum limits from the international standards used in the original study, including standards attributed to ANSES and the European Commission. Because the reported results for the analyzed metals were expressed as values below the analytical detection thresholds, interpretation focused on whether the measured concentrations exceeded or remained below the reference limits. No inferential statistical comparison among the geographic sources was performed or reported in the source manuscript.

4. Results and Discussion

4.1 Heavy-Metal Concentrations in *Caulerpa lentillifera*

The laboratory analysis determined the concentrations of arsenic (As), lead (Pb), cadmium (Cd), and mercury (Hg) in *Caulerpa lentillifera* samples sold in selected markets in Sampaloc, Manila, with declared geographic origins from Batangas, Cebu, and Marinduque. The results for the three sources are consolidated in Table 1.

Table 1 Heavy-Metal Concentrations in *Caulerpa lentillifera* According to Declared Geographic Origin

Analyte	Batangas	Cebu	Marinduque	Reference Maximum Limit
Arsenic (As), ppm	<0.3	<0.3	<0.3	3
Lead (Pb), ppm	<0.3	<0.3	<0.3	5
Cadmium (Cd), ppm	<0.1	<0.1	<0.1	0.5 / 0.3
Mercury (Hg), ppm	<0.03	<0.03	<0.03	0.1

Note. Reference maximum limits are those reported in the original study from ANSES and European Commission standards.

As shown in Table 1, arsenic concentrations in all three samples were reported as below 0.3 ppm. This value was substantially below the reference maximum limit of 3 ppm used in the study. The lead concentrations were similarly below 0.3 ppm for all samples, compared with the reference maximum limit of 5 ppm.

Cadmium concentrations were below 0.1 ppm in samples from all three declared geographic origins. These results were below the reference limits of 0.5 ppm and 0.3 ppm adopted by the study. Mercury concentrations were also below the analytical detection threshold of 0.03 ppm, which was lower than the reference maximum limit of 0.1 ppm.

The results therefore indicate that none of the four target metals was detected at a concentration approaching the international maximum limits used as benchmarks in the study. Within the sensitivity of the analytical procedures employed, the tested samples demonstrated low measurable contamination from arsenic, lead, cadmium, and mercury.

4.2 Comparison Across Declared Geographic Sources

The reported analytical results were consistent across the samples identified as originating from Batangas, Cebu, and Marinduque. For each geographic source, arsenic was reported below 0.3 ppm, lead below 0.3 ppm, cadmium below 0.1 ppm, and mercury below 0.03 ppm.

These findings should, however, be interpreted cautiously. Because all reported concentrations were expressed as values below the corresponding analytical detection thresholds, the results do not establish that the actual concentrations were identical across the three geographic sources. For example, a result reported as below 0.3 ppm indicates only that the analyte concentration was lower than the laboratory's reporting threshold; it does not specify the precise concentration below that level.

Consequently, no statistical or substantive conclusion regarding geographic differences can be established from the available data. The findings instead demonstrate that all analyzed samples fell below the respective detection thresholds and below the international maximum limits adopted for comparison. This distinction is particularly important in environmental and food-safety studies because nondetectable or below-detection-limit results should not be interpreted as complete absence of a contaminant. Rather, they indicate that the contaminant, if present, occurred at concentrations that could not be quantified above the analytical threshold used in the study.

4.3 Food-Safety Implications

The low reported concentrations of arsenic, lead, cadmium, and mercury have favorable implications for the food safety of the *C. lentillifera* samples examined. All measured values were below the international reference maximum limits used in the study, suggesting that the tested products did not exhibit heavy-metal contamination at levels considered unacceptable under those comparative standards.

This finding is relevant because edible seaweeds can accumulate metals and other substances from their surrounding environment. Previous studies have emphasized that the food-safety evaluation of seaweed should account for both its nutritional benefits and the potential accumulation of undesirable contaminants (Banach et al., 2020; Cherry et al., 2019). Likewise, studies of edible seaweeds from different regions have demonstrated that heavy-metal concentrations can vary considerably depending on species, environmental conditions, and exposure to contaminant sources (Filippini et al., 2021; Hahn et al., 2022; Lee et al., 2022).

The present results suggest that the *C. lentillifera* samples analyzed did not contain arsenic, lead, cadmium, or mercury at concentrations exceeding the adopted safety benchmarks. However, the findings should not be generalized to all *C. lentillifera* sold in Manila or produced in Batangas, Cebu, and Marinduque because the study examined only the available samples described in the source manuscript. The results therefore represent the condition of the analyzed samples rather than a comprehensive assessment of seaweed production in the three geographic areas.

Continued monitoring remains appropriate because seaweed contamination may vary over time and across harvesting locations. Environmental conditions, proximity to industrial or mining activity, water quality, sediment contamination, and coastal development can influence metal concentrations in marine environments. Routine testing of edible seaweeds can therefore contribute to consumer protection and provide evidence for the development of more specific local food-safety standards.

4.4 Implications for Bioremediation

The capacity of seaweeds to interact with dissolved substances and accumulate metals from aquatic environments has led to their investigation as possible biomonitoring and bioremediation organisms. Previous literature has described seaweeds as potential indicators of heavy-metal contamination and as possible biological agents for contaminant sequestration (Roleda & Hurd, 2019; Van Ginneken & De Vries, 2018).

The present findings, however, do not directly demonstrate the bioremediation efficiency of *C. lentillifera*. Because the analyzed samples contained metal concentrations below the analytical detection thresholds, the study did not quantify metal uptake rates, removal efficiency, accumulation capacity, exposure-response relationships, or tolerance under contaminated conditions.

Accordingly, the phrase "basis for bioremediation" is most appropriately interpreted as a basis for further investigation rather than evidence that *C. lentillifera* has already been demonstrated to function as an effective remediation agent. Future experimental studies could expose *C. lentillifera* to controlled concentrations of selected metals and measure changes in metal concentrations in the surrounding medium and seaweed tissues over time. Such studies would provide stronger

evidence regarding sequestration capacity and potential remediation efficiency. This distinction between preliminary screening evidence and demonstrated functional efficacy parallels methodological cautions raised in other in-vitro bioactivity research, where laboratory-scale findings are treated as a starting point for, rather than proof of, practical application (Diaz et al., 2025).

4.5 Discussion

The principal finding of the study is that arsenic, lead, cadmium, and mercury concentrations in the analyzed *C. lentillifera* samples were below the laboratory reporting thresholds and below the international maximum limits used for comparison. From a food-safety perspective, the results provide no evidence of elevated contamination by the four metals examined in the tested samples.

This finding is consistent with the broader literature showing that the presence and concentration of metals in edible seaweeds depend strongly on species, environmental exposure, and geographic conditions. Seaweeds are capable of accumulating elements from their surroundings, but accumulation does not necessarily occur at concentrations that constitute a health concern (Hahn et al., 2022; Lee et al., 2022). Consequently, measured concentrations must be assessed against appropriate safety standards rather than interpreted solely on the basis of whether a metal can theoretically be accumulated.

The results also reinforce the value of market-based food-safety monitoring. Seaweed purchased in urban markets may originate from geographically distant production areas, as reflected by the declared origins of Batangas, Cebu, and Marinduque in the present study. Monitoring products at the point of sale can therefore complement environmental assessments conducted directly at aquaculture or harvesting sites by providing information on products that actually reach consumers.

At the same time, the analytical structure of the findings limits the conclusions that can be drawn. Because all four metals were reported only as below specific detection thresholds, the study cannot determine the precise concentrations present or establish whether meaningful differences existed among the three declared geographic sources. The results should therefore be interpreted as evidence of concentrations below the study's analytical reporting limits rather than evidence of complete absence of heavy metals.

The findings nevertheless provide useful baseline information for environmental health and food-safety monitoring. They also identify a logical direction for subsequent research on the metal-accumulation characteristics of *C. lentillifera*. Given the recognized ability of seaweeds to absorb substances from surrounding waters, controlled experimental investigations could determine whether this species has sufficient uptake capacity to support practical bioremediation applications. In this sense, the present study contributes preliminary analytical evidence while distinguishing food-safety assessment from the more demanding experimental requirements necessary to establish bioremediation effectiveness.

5. Conclusions, Recommendations, and Implications

5.1 Conclusions

This study determined the concentrations of arsenic (As), lead (Pb), cadmium (Cd), and mercury (Hg) in *Caulerpa lentillifera* sold in selected markets in Sampaloc, Manila, with samples identified as originating from Batangas, Cebu, and Marinduque.

The laboratory results showed that arsenic concentrations were below 0.3 ppm, lead concentrations were below 0.3 ppm, cadmium concentrations were below 0.1 ppm, and mercury concentrations were below 0.03 ppm for all analyzed samples. These reported values were below the international maximum limits used as comparative benchmarks in the study.

Based on these findings, the analyzed *C. lentillifera* samples did not show evidence of elevated contamination by the four heavy metals examined. Within the analytical limits of the methods employed, the results indicate a low level of detectable heavy-metal contamination and suggest that the tested samples did not present an apparent food-safety concern in relation to arsenic, lead, cadmium, and mercury.

The consistency of the reported results across the three declared geographic sources should not, however, be interpreted as proof that the actual heavy-metal concentrations were identical. Because all results were reported below the corresponding analytical detection thresholds, the study cannot establish precise quantitative differences among the samples.

The findings also provide baseline information relevant to the possible environmental applications of *C. lentillifera*. However, the present study did not directly measure metal-removal efficiency, accumulation capacity, uptake rate, or remediation performance. The results therefore serve only as an initial basis for further investigation of the potential use of *C. lentillifera* in heavy-metal monitoring and bioremediation.

5.2 Recommendations

Routine monitoring of edible *C. lentillifera* and other commercially distributed seaweeds is recommended to help ensure continued food safety, particularly in products sourced from areas potentially influenced by industrial activity, mining, urbanization, agricultural runoff, or other sources of aquatic contamination.

Future studies should include a larger and more clearly documented sampling framework that identifies the number of samples collected, their precise points of purchase, declared places of origin, collection periods, and, where applicable, harvesting or production sites. Repeated sampling across locations and time periods would provide a stronger basis for evaluating geographic and temporal variation in heavy-metal concentrations.

Additional laboratory studies may also employ analytical procedures capable of reporting lower detection and quantification limits. Such approaches could provide more precise concentration estimates when contaminant levels fall below the reporting thresholds observed in the present study. Broader capacity-building efforts, such as workforce readiness for technology-assisted diagnostic and analytical procedures in Philippine laboratory settings, may likewise support the wider adoption of more sensitive detection methods over time (Fernandez et al., 2026).

The development or refinement of Philippine regulatory guidelines specific to heavy-metal concentrations in edible seaweeds should also be considered. Locally applicable standards would provide a clearer basis for food-safety monitoring, regulatory enforcement, and consumer protection.

Further experimental research is recommended before *C. lentillifera* is considered for practical bioremediation applications. Controlled studies should determine its metal-uptake capacity, accumulation rate, tolerance to contaminated environments, removal efficiency, and performance across different concentrations of target contaminants.

5.3 Implications of the Study

The study has practical implications for food safety, environmental health, marine-resource management, and future bioremediation research. The low reported concentrations of arsenic, lead, cadmium, and mercury in the analyzed samples provide preliminary evidence that the tested *C. lentillifera* products were within the international comparison limits applied in the study.

From a public-health perspective, the findings underscore the value of monitoring edible marine products at the point of sale. Because seaweed distributed in urban markets may originate from geographically distant production areas, market-based testing can complement environmental monitoring conducted directly in coastal or aquaculture locations.

From an environmental-management perspective, the study demonstrates the relevance of seaweed as a biological material for monitoring potential contaminant exposure. Its direct interaction with aquatic environments makes *C. lentillifera* a useful organism for further investigation in studies examining metal accumulation and environmental contamination.

The study also has regulatory implications. The absence of clearly specified local limits for heavy metals in edible seaweed highlights the importance of developing context-appropriate Philippine standards and monitoring protocols for marine food products.

Finally, the findings provide a preliminary research foundation for examining *C. lentillifera* in relation to bioremediation. While the present results do not establish remediation effectiveness, they support further controlled investigation of the species' capacity to accumulate, sequester, or remove heavy metals from contaminated aquatic environments.

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