Original Article

Low mercury content in Seychelles seaweed: implications for aquaculture expansion

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Abstract
Stable tropical conditions and a near-pristine marine environment in the Seychelles suggest a high potential for seaweed aquaculture to supply growing global markets for sustainable marine products. The aims of this study were to assess the mercury content in five seaweed species that are candidates for aquaculture in Seychelles: *Gracilaria cortica*, *Gracilaria salicornia*, *Caulerpa racemosa*, *Sargassum* spp., and *Asparagopsis taxiformis*. Mercury contamination is a significant concern in seaweed aquaculture because it may bioaccumulate, potentially affecting human health when derived products are used. Samples were collected from different sites in Seychelles, categorized as polluted or unpolluted, to evaluate the influence of environmental factors on mercury accumulation. The results showed that mercury contents were low across all tested seaweed species and sites, with the highest observed content of 0.0038 mg/kg (wet weight), well below international safety limits. Significant differences were found between species; however, site pollution level did not significantly influence mercury content. Low mercury content, in addition to a favourable physical environment, confirm that the region is suitable for seaweed aquaculture. It is recommended that other heavy metal concentrations are also assessed, to provide a comprehensive safety evaluation of seaweed aquaculture in Seychelles.

Keywords: mercury, aquaculture, seaweeds, heavy metals, bioaccumulation, pollution

Introduction
Seaweed aquaculture is the fastest-growing sector in global aquaculture, driven by the increasing demand for various sustainable products such as food, animal feed, nutraceuticals, cosmetics, and biostimulants (Duarte *et al.*, 2022). In this context, the Seychelles, with its unspoiled marine ecosystems and extensive coastal resources, presents an ideal setting for the cultivation of commercially viable seaweed species. The country's advantageous geographic location, situated outside the cyclone belt, combined with its favourable and stable climatic conditions, further enhances its suitability for tropical seaweed farming. Additionally, the Seychelles government's proactive approach to sustainable aquaculture, as part of its broader blue economy strategy, reinforces the nation's potential to expand its seaweed aquaculture sector responsibly and successfully. However, as with any emerging industry, careful consideration of food safety standards is essential to ensure the long-term viability of seaweed aquaculture and general human health.

Mercury contamination poses a significant concern in marine food webs, particularly due to its ability to bioaccumulate and biomagnify, leading to potentially harmful effects on both ecosystems and human health

(Lavoie *et al*., 2013). In aquatic environments, mercury can originate from various sources, including industrial emissions, agricultural runoff, and natural processes such as volcanic activity and weathering of rocks (Driscoll *et al*., 2013). Once in the ocean, mercury can be transformed into its more toxic form, methylmercury, which is readily absorbed by marine organisms, including seaweeds (Lavoie *et al*., 2013). This process raises concerns about the potential for mercury contamination in seaweed products intended for human consumption or use in aquaculture.

Although the Seychelles is considered a relatively pristine environment, its proximity to shipping routes, industrial zones, and tourism activities could introduce mercury into the marine ecosystem. Previous studies on mercury levels in the Seychelles have primarily focused on fish, with results indicating similar levels of mercury compared to those in other regions (Robinson and Shroff, 2020; Stern *et al*., 2004; Zareba *et al*., 2023). Before investing further in seaweed aquaculture development, it is crucial to thoroughly assess mercury contents to ensure they remain within safe limits. If mercury levels are found to be too high, it could undermine the viability of expanding seaweed farming, making it a less sustainable or profitable option for development. High mercury levels could lead to the rejection of seaweed products in export markets, as international safety standards require mercury content to be below 0.5 mg/kg for most food products, including seafood (World Health Organization, 2014), but the EU has recently lowered this limit to 0.3 mg/kg (The European Commission, 2022).

In this study, five species of seaweed that hold commercial potential in the Seychelles are focussed on: *Gracilaria cortica*, *Gracilaria salicornia, Caulerpa racemosa*, *Sargassum spp.*, and *Asparagopsis taxiformis*. Each species is targeted for its unique properties and applications. *Gracilaria cortica* and *Gracilaria salicornia* are of particular interest for their applications in food, pharmaceuticals, and cosmetics (L. Mattio, independent consultant, personal communication, 2024; Francavilla *et al*., 2013; Lee *et al*., 2022; Somasiri *et al*., 2017). *Caulerpa racemosa*, commonly known as sea grapes, is prized as a fine dining ingredient, offering a promising opportunity for local consumption in Seychelles' high-end hotels. *Sargassum spp*. are being explored for their use in fertilizers and animal feed, while *Asparagopsis taxiformis* has gained attention for its potential in reducing methane emissions when used as a feed additive for livestock (Roque *et al*., 2021). Given their diverse applications, ensuring the safety of these species, particularly regarding heavy metal contamination, is paramount.

Analysing the mercury content in these seaweeds is crucial due to their potential for mercury accumulation, which can have significant health implications for consumers. Although there is limited data on the specific seaweed species found in the Seychelles, research on related genera has shown varying mercury contents in different seaweed species depending on their habitat, season, and environmental conditions (Paz *et al*., 2019). For example, *Halopteris filicina* and *Peyssonnelia squamaria* have shown mercury contents near regulatory limits set by the EU for food and feed, with levels reaching up to 0.1 mg/kg (Squadrone *et al*., 2018). Even higher mercury levels haves been recorded in *Ecklonia radiata*, reaching 0.17 mg/kg (Smith *et al*., 2010), underscoring the variability of mercury bioaccumulation across seaweed species. Therefore, evaluating mercury levels in Seychelles' seaweeds is essential for ensuring product safety, market acceptance, and sustainable aquaculture development in the region.

To address these concerns, this study is the first to investigate mercury contents in five commercially important seaweed species collected from areas considered to be high and low in pollution across Mahé Island. It is aimed to answer critical questions regarding the influence of species, collection site, and water quality on mercury accumulation in the seaweeds. The findings provide valuable insight into the safety of seaweed products in the Seychelles and contribute to the sustainable development of the country's aquaculture industry.

Methods

Seaweed collection

Seaweeds were collected on the 22nd of August 2024 from various locations around Mahe, Seychelles (Table 1). Certain locations were classified as polluted or unpolluted based on their proximity to industrial or highly populated areas. Water quality tests (described below) were conducted to assess how polluted the sites were. Samples were collected by snorkelling or wading. Latex gloves were used during collection to prevent contamination. At each site, samples were taken from at least three sub populations that were spatially separate from each other. At least 10 g of each sample was collected. Each seaweed sample was kept in 1 L sample bottles that had been sterilized and thoroughly washed with distilled water. The bottles were kept in a cooler

Table 1. Description and co-ordinates of seaweed collection sites around Mahé Island, Seychelles, with details on habitat characteristics, anthropogenic influence, pollution classification, and seaweed species collected. Sites were categorized as polluted or unpolluted based on proximity to human activity and industrial zones, with further support from water quality assessments.

Site	Description	Anthropogenic influence	Considered	Seaweeds collected
La Retraite (4°35'11.42"S, 55°27'44.65"E)	Artificial estuary with shallow (1-2 m) muddy bottom.	High population density with significant boat traffic. Waste discharge increases during heavy rainfall.	Polluted	*G. salicornia*
Marine park (4°37'17.26"S, 55°30'33.22"E)	Sandy flats (1-2 m) with broken rocky reef and occasional coral patches.	Located in a marine protected area, distant from heavy boat traffic and tourism activities.	Unpolluted	*A. taxiformis* (gametophyte)
Perseverance (4°36'12.62"S, 55°28'1.88"E)	Artificial granite retaining wall facing a shallow coral reef.	Artificial granite retaining wall facing a shallow coral reef.	Unpolluted	*C. racemosa* *G. cortica*
Providence (4°39'8.07"S, 55°29'42.14"E)	Unutilized fish cage overgrown with biofoulers in 15 m deep water with soft, muddy, and anoxic sediment, previously dredged.	Near Seychelles' industrial zone and waste dump. Elevated levels of heavy metals like nickel have been observed in the water (2.5mg/l; personal observation 2024)	Polluted	*G. cortica* *C. racemosa* *Sargassum spp.*
Port Glaud (4°39'53.01"S, 55°24'54.93"E)	Shallow (1-2 m) rocky reef flat behind a barrier reef.	Low human population, no industrial activity, and minimal human influence.	Unpolluted	*G. salicornia*
Anse Forbans (4°46'43.63"S, 55°31'26.13"E)	Shallow (1-2 m) rocky reef flat behind a barrier reef.	Low human population, no industrial activity, and minimal human influence.	Unpolluted	*A.taxiformis* (gametophyte) *Sargassum spp.*

box at approximately 20 °C. The bottles with the samples were kept overnight in the Seychelles Fisheries Authority microalgae production facility room at 21 °C with gentle aeration. No degradation of any seaweed samples was observed between collection and analysis.

Water quality sampling

Dissolved oxygen (DO) and temperature were measured on site using a Hach HQ1130 portable water quality meter, which was calibrated prior to use. Water samples at each site were collected in 1 L sample bottles that were sterilized and washed with distilled water prior to sample collection. The bottles were kept in a cooler box at approximately 20 °C. One to four hours after collection, the water samples were tested for total ammonia nitrogen (TAN), nitrate, nitrite and phosphate. This was done photometrically using a Palintest Photometer 7100. For the TAN tests, lithium hydroxide was used to condition the seawater prior to using AP152 tablet reagents. The reagents used for nitrate, nitrite and phosphate were AP109, AP163 and AP177 respectively.

Mercury analysis

The mercury content of the seaweed samples was analysed at the Seychelles Fisheries Authority's Product Development and Quality Assurance Laboratory using a direct determination method for solid samples. Each seaweed and site sample had three replicates. To reduce the intra-site variability, the seaweeds were homogenised with a commercial blender prior to analysis. The mercury determination was conducted using a Milestone DMA-80 mercury analyser, following the guidelines outlined in EPA method 7473. This specific analyser enables the detection of total mercury in both solid and liquid samples without requiring any pre-treatment. Samples were weighed and placed in quartz boats, which were loaded into the instrument's autosampler. The boats were then introduced into an oxygen-enriched decomposition furnace, where samples were dried and decomposed. During this process, the combustion products were carried through a heated catalyst, which reduced mercury species to their elemental form, while trapping halogens, nitrogen oxides, and sulphur oxides. The mercury vapour was concentrated in a gold amalgamator, then released into the absorbance cells, where it was quantified at a wavelength of 253.7 nm. The detection limit of this method was approximately 0.00001 mg/kg.

Statistical analysis

Statistical tests were conducted to determine whether mercury levels in seaweed were influenced by species, site, or water chemistry. A Kruskal-Wallis rank sum test

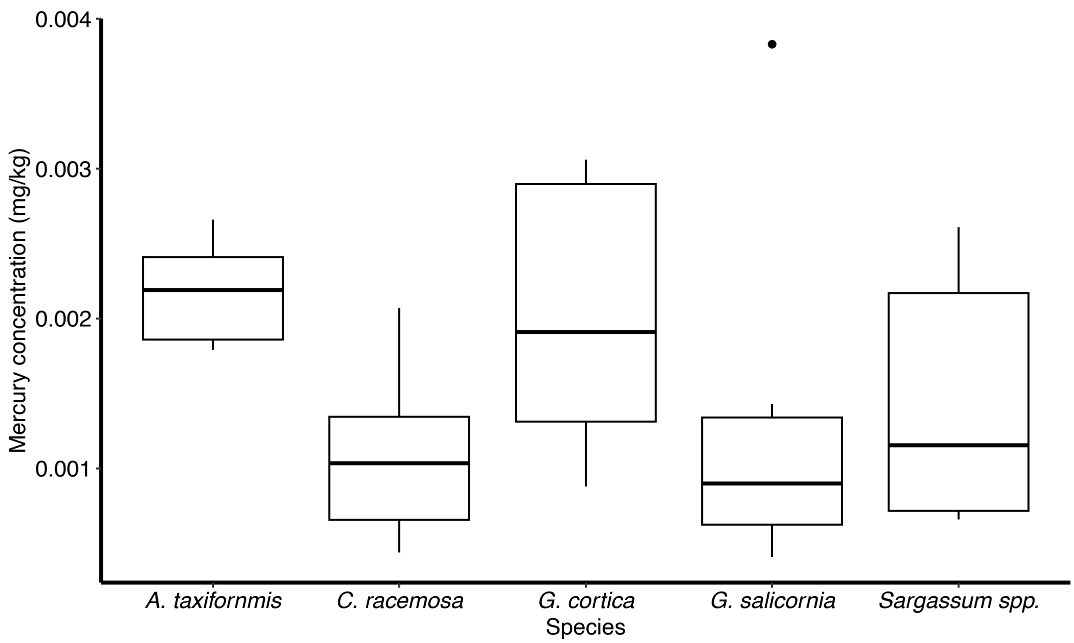

Figure 1. Boxplot illustrating mercury content (mg/kg) across different seaweed species. The x-axis represents the seaweed species: Asparagopsis taxiformis, Caulerpa racemosa, Gracilaria cortica, Gracilaria salicornia, and Sargassum spp.. The y-axis shows the mercury content observed in the samples, with each boxplot representing the range of contents for each species. In each boxplot, the box represents the interquartile range (IQR), the line inside the box indicates the median value, and the whiskers extend to the minimum and maximum values within 1.5 times the IQR. The grey symbol represents an outlier.

was used to evaluate differences in mercury content among the various seaweed species, chosen due to the non-normal distribution of data (Shapiro-Wilk; $p < 0.05$) and the presence of outliers. One outlier, which had the highest observed mercury content of 0.0055 mg/kg in *Asparagopsis taxiformis* from Anse Forbans, was excluded from analysis due to suspected contamination from residual mercury in the analyser as it was the first sample processed. Another outlier that had no logical explanation was left in the statical analysis.

Correlation analysis was performed to assess the relationship between mercury contents and various water quality parameters, including dissolved oxygen, total ammonia nitrogen, nitrate, phosphate, and nitrite, to evaluate potential associations between water quality and mercury accumulation. Additionally, a Shapiro-Wilk test confirmed that the data for polluted and unpolluted sites were approximately normally distributed ($p > 0.05$), allowing a two-sample t-test to compare mean mercury contents between the two groups of sites.

Results

The average mercury content observed amongst all seaweed species and sites was 0.0017mg/kg (wet weight). The highest mercury content was found in a sample of *G. salicornia* from Port Glaud, at 0.0038 mg/kg. This site, and species exhibited high variability, as another sample of *G. salicornia* showed the lowest mercury content recorded for any sample, at 0.0004 mg/kg (Fig. 1). The species of seaweed had a significant influence on mercury content ($H = 10.686$, $df = 4$, $p = 0.030$), where *A. taxiformis and G. cortica* had, on average, the greatest mercury content.

The Providence site, considered polluted due to its proximity to the island's waste landfill, showed the highest median mercury content (0.0019 mg/kg). However, Providence also showed the second lowest mercury content in one of its samples (*C. racemosa*, 0.0004 mg/kg), indicating high variability within the site. While the marine park appeared to have consistently higher mercury content, it should be noted that it had a smaller sample size (n = 3) compared to the other sites. Overall, the observed differences in mercury contents across sites were not statistically significant ($H = 6.962$, $df = 5$, $p = 0.224$; Fig. 2). This suggests that site location did not have a significant effect on mercury accumulation in the seaweed samples.

The correlation analysis revealed several important relationships between mercury content in seaweed and the measured water quality parameters (Fig. 3).

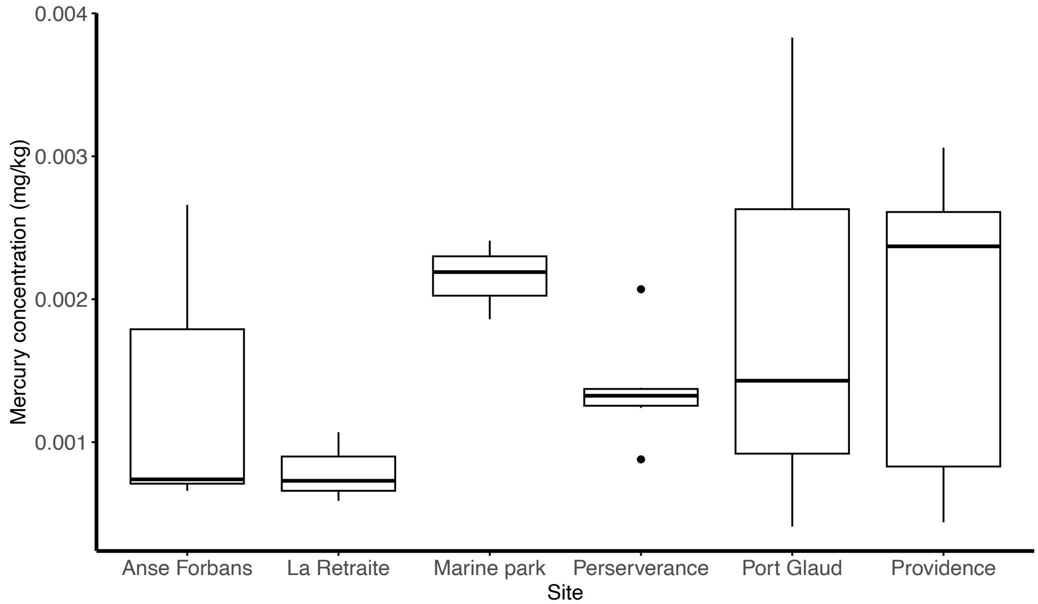

Figure 2. Boxplot illustrating mercury content (mg/kg) in seaweed samples collected from various sites. The x-axis represents the different collection sites which are described in more detail in Table 1.

Notably, mercury content exhibited strong negative correlations with both temperature (r = -0.81) and phosphate content (r = -0.88). This suggests that higher temperatures and increased phosphate levels may be associated with lower mercury content in seaweed samples. Additionally, a moderate negative correlation was observed between mercury content and dissolved oxygen (DO) levels (r = -0.60), implying that higher dissolved oxygen may also be linked to reduced mercury accumulation. Other parameters,

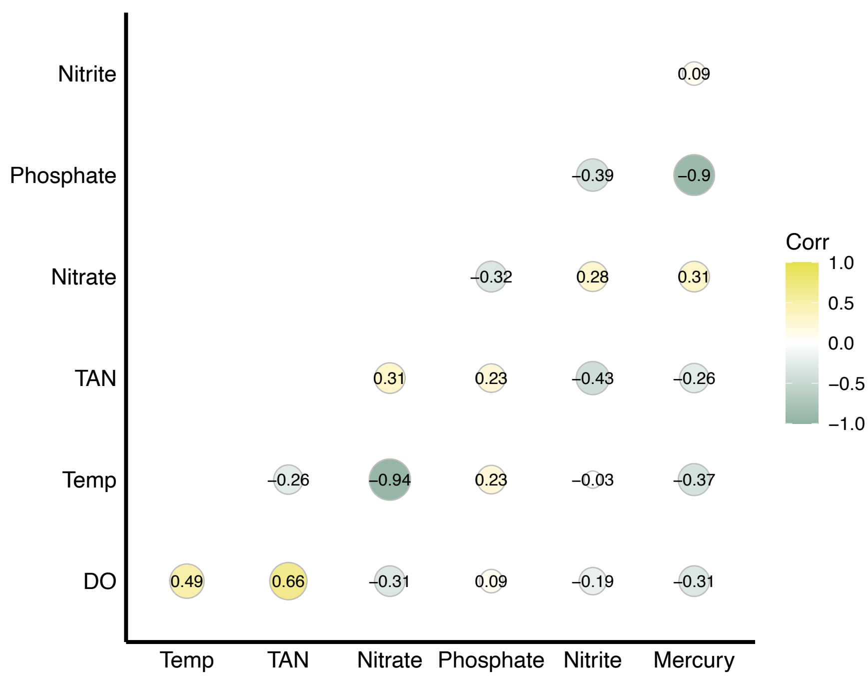

Figure 3. Correlation heatmap showing the relationships between water quality parameters and average mercury content (mg/kg) across all seaweed samples collected at each site. The water quality parameters include dissolved oxygen (DO), temperature (Temp), total ammonia nitrogen (TAN), nitrate, phosphate, and nitrite. The mercury content represents the average for all seaweed samples at each site. Positive correlations are shown in red, negative correlations in blue, and the colour intensity reflects the strength of the correlation. The values indicate the Spearman correlation coefficient for each relationship.

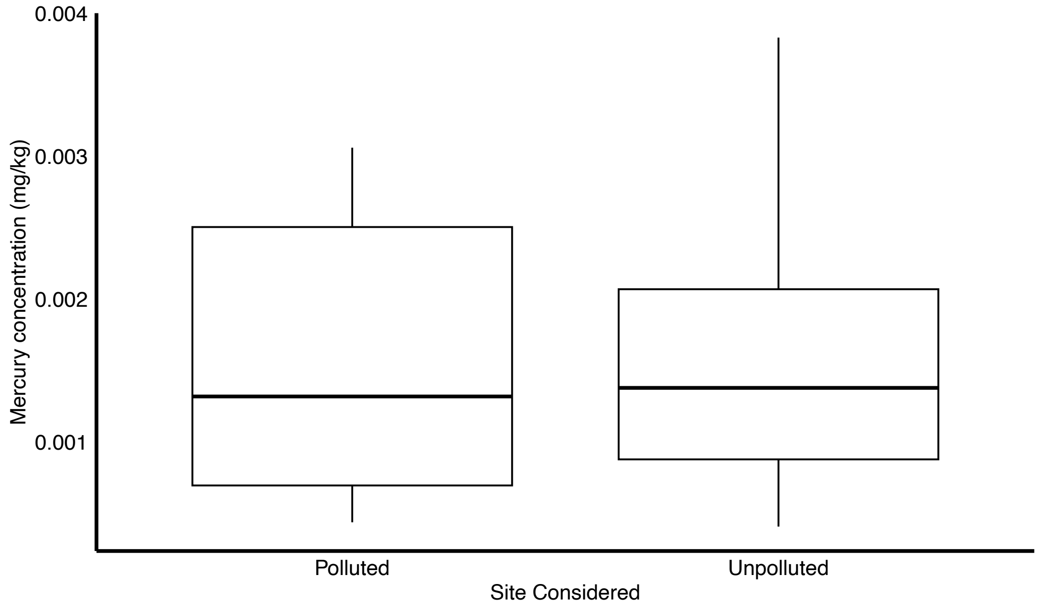

Figure 4. Boxplot comparing mercury content (mg/kg) between seaweed samples of various species collected from six different sites around Mahé Island, Seychelles, where sites are considered polluted or unpolluted based on anthropogenic activities in the area (as described in Table 1).

such as total ammonia nitrogen (TAN) and nitrite, exhibited very weak correlations with mercury content (r = -0.04 and r = 0.02, respectively), indicating a limited influence on mercury levels in seaweed. A strong negative correlation between temperature and total ammonia nitrogen (TAN, r = -0.94) was evident.

The objective was to determine if areas considered as polluted influenced mercury contents in seaweed samples. A t-test found no significant difference between polluted and unpolluted sites (t = 0.0908, df = 27, p = 0.9284). The mean mercury contents were nearly identical for both groups (polluted: 0.00162 mg/kg, unpolluted: 0.00158 mg/kg, Fig. 4). Similarly, there was no indication that other water chemistry parameters differed between sites considered polluted or unpolluted.

Discussion

The results of this study indicate that mercury contents in the seaweeds collected from the Seychelles are extremely low across all species and collection sites. The greatest mercury content observed was in *Gracilaria salicornia* at 0.0038 mg/kg (wet weight), which is well below the international safety standards of 0.5 mg/kg set by the World Health Organization (2014) and below the newly lowered EU limit of 0.3 mg/kg (The European Commission, 2022). These results suggest that even in the worst-case scenario observed in this study, the mercury content is well below thresholds of concern. Consequently, the risk of mercury poisoning from the consumption of seaweeds in the Seychelles appears negligible, implying that the expansion of seaweed aquaculture in the region can be safely pursued.

It is notable that significant differences were found in the mercury content amongst different seaweed species, with *Gracilaria cortica* and *Asparagopsis taxiformis* exhibiting higher average mercury content compared to other species. Similar findings have been reported in other studies, where species differences significantly influenced mercury accumulation (Paz *et al.*, 2019; Smith *et al.*, 2010). This interspecies variation suggests differences in mercury uptake capabilities, potentially related to species-specific biological factors or habitat preferences. However, the most important takeaway is that all mercury contents observed are very low, and such interspecies variability does not present any risk of mercury contamination.

Interestingly, these findings show that site location did not have a significant influence on mercury content in seaweeds. Even the sample with the highest mercury content came from a site (Port Glaud) considered to be 'unpolluted' due to low anthropogenic influence. This site also had the lowest mercury content observed, indicating high variability within the same location. Overall, no statistically significant differences were found in mercury contents between sites classified as polluted or unpolluted, suggesting that current perceptions of pollution may not accurately predict mercury accumulation in seaweeds.

This study represents a snapshot of the mercury content in seaweeds and corresponding water quality parameters. Longer-term sampling of both water quality and mercury contents would be beneficial for a more comprehensive understanding of these dynamics. Additionally, future studies should include the analysis of other heavy metals, such as arsenic, to ensure a thorough assessment of human health safety. This is the first study to examine mercury content in seaweeds from the Seychelles, and it provides important preliminary insights that there is no evidence that mercury content in these seaweeds pose any risk for human consumption. Therefore human consumption, as well as aquaculture production of these seaweed species, could be undertaken without concern.

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