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Health Risk Assessment of Lead (Pb) and Copper (Cu) Contamination in Sediments of Palu Bay, Indonesia

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Heavy metals are persistent environmental pollutants that tend to accumulate in coastal sediments and may pose long-term ecological and human health risks. This study evaluated the concentrations of lead (Pb) and copper (Cu) in surface sediments of Palu Bay, Central Sulawesi, Indonesia, and assessed potential non-carcinogenic and carcinogenic health risks through dermal exposure. Sediment samples were collected from ten stations representing residential areas, ports, river estuaries, and relatively open zones. Concentrations of Pb and Cu were analyzed using Atomic Absorption Spectrophotometry (AAS) after acid digestion. Sediment contamination was evaluated using the contamination factor (CF) and geoaccumulation index (Igeo), while human health risk assessment (HRA) followed U.S. EPA guidelines. Mean concentrations of Pb and Cu were 6.61 ± 3.64 mg/kg and 20.70 ± 8.83 mg/kg, respectively, and were below international sediment quality guidelines (CCME and ANZECC). CF values (<1) and negative Igeo values indicated low contamination levels. The hazard quotient (HQ) and hazard index (HI) for dermal exposure were below the threshold of concern (HI < 1), suggesting no significant non-carcinogenic risk. Carcinogenic risk (CR) for Pb was within the acceptable range (10^{-6}–10^{-4}). Overall, surface sediments in Palu Bay show low levels of Pb and Cu contamination and currently pose minimal health risk through dermal contact. The results provide baseline data to support future monitoring and coastal management strategies.

Keywords: Heavy Metals, Lead, Copper, Sediment, Human Health Risk

INTRODUCTION

Palu Bay is a strategic coastal area in Central Sulawesi that serves as a source of fisheries, marine transportation, and a center of community economic activities. Human activities around the coast include fisheries, agriculture, port operations, and settlements, all of which have the potential to contribute pollutants to the marine environment (Effendi et al., 2016; Tang et al., 2022). One of the most hazardous pollutants is heavy metals, as they are toxic, persistent, and capable of accumulating within ecosystems (Jaishankar et al., 2014). Coastal sediments act as the primary reservoir of heavy metals, making them a more stable indicator of pollution compared to seawater (Khaled et al., 2017; Naik et al., 2023). The accumulation of heavy metals in sediments can also serve as a secondary source of exposure for aquatic organisms and humans (Sojka et al., 2023). This condition highlights the importance of sediment quality studies as a basis for evaluating both environmental and health risks (Fadlillah et al., 2023).

Heavy metals such as lead (Pb) and copper (Cu) are commonly associated with industrial, agricultural, and domestic activities (Ismanto et al., 2024; Tampubolon et al., 2021). Lead is a non-essential metal and is highly toxic even at low concentrations, potentially causing neurological disorders, kidney damage, and developmental impairments in children (Jaishankar et al., 2014). Copper, although an essential trace element for biological processes, can exert toxic effects on the liver and kidneys when present in excessive amounts (Kuang et al., 2021). Previous studies in Indonesia have shown that heavy metals are widely present in coastal waters due to anthropogenic activi ties. For example, research in Jakarta Bay revealed high accumulation of heavy metals as a result of domestic and industrial waste, while studies in Ambon Bay reported Pb concentrations in sediments exceeding threshold limits, posing both ecological and health risks (Budiyanto & Lestari, 2017; Tupan & Uneputty, 2017). These findings indicate that Indonesian coastal areas are highly vulnerable to heavy metal pollution.

Sediments play a crucial role in the heavy metal cycle because they can absorb and release metals back into the water column depending on environmental conditions (Bhuyan et al., 2023; Enuneku & Ineh, 2020).

Changes in pH, dissolved oxygen, and microbial activity can cause metals to re-dissolve into the aquatic system. This increases the potential for exposure to aquatic organisms (Upadhyay et al., 2025) and humans through the food chain (Riani et al., 2018). Bioaccumulation and biomagnification processes lead to the presence of heavy metals in the tissues of organisms, including fish frequently consumed by local communities (Rongxi et al., 2020). Consequently, coastal populations may be exposed to heavy metals not only through direct contact with water but also through seafood consumption. This health risk underscores the need for a comprehensive assessment using a risk-based approach. Thus, sediments serve not only as indicators of pollution but also as a key factor in human health risk analysis (Putri et al., 2025).

Human Health Risk Assessment (HRA) is a quantitative approach to evaluating the potential health impacts of exposure to hazardous substances (Enuneku & Ineh, 2020; Handayani et al., 2025; Kissar & Khemmoudj, 2025; Miletić et al., 2023). The US EPA has developed a standard method that includes the calculation of Chronic Daily Intake (CDI), Hazard Quotient (HQ), and Hazard Index (HI) (EPA, 1989). HQ is used to assess the non-carcinogenic risk of heavy metals by comparing the daily dose with the Reference Dose (RfD). If HQ < 1, the health risk is considered low, while HQ > 1 indicates a potential risk. Meanwhile, the HI represents the sum of HQ values for multiple metals, providing an overview of the combined risk from different contaminants. Through this approach, the potential hazards of Pb and Cu in Palu Bay can be evaluated in relation to public health.

Research on heavy metal pollution in Palu Bay has been conducted previously; however, most studies have focused on seawater and marine biota (Paundanan et al., 2015), or limited to the analysis of heavy metal (Pb, Cd and Cu) content in water and sediments without assessing the potential health risks (Paundanan et al., 2025). Specific studies on sediments and their implications for human health risk remain scarce. In fact, sediments are an important medium that records long-term pollution and functions as a reservoir for heavy metals. Therefore, this study was conducted to assess the concentrations of Pb and Cu in Palu Bay sediments and to perform a health risk assessment for the coastal communities. This research is expected to provide a more comprehensive understanding of the environmental conditions of Palu Bay. Moreover, the findings can serve as a foundation for environmental management and public health policy development.

METHOD

Study area

This study was conducted in Palu Bay, Central Sulawesi, Indonesia, a coastal area characterized by high levels of anthropogenic activities. Sediment samples were collected from 10 observation stations representing areas near settlements, ports, river estuaries, and relatively open zones. Sampling was carried out on surface layers using a PVC pipe with a diameter of approximately 5 cm, inserted into the sediment up to a depth of about 20 cm. The upper layer (0–10 cm) was taken because it is the most susceptible to recent contamination and represents the contact zone with benthic organisms. The collected samples were placed in clean plastic bags, labeled according to the station, and stored in a cool box to prevent changes in chemical properties. All samples were then transported to the laboratory for drying, preparation, and heavy metal analysis.

Analysis Heavy Metals

The analysis of Pb and Cu in sediment samples was carried out at the UPTD Laboratory for Testing and Quality Certification, Office of Industry and Trade of Central Sulawesi Province, which is accredited for environmental quality testing. Sediment samples were first dried at 105 °C until constant weight was achieved to remove moisture content. The dried sediments were then ground into fine powder, homogenized, and sieved using a 63 µm mesh to ensure uniform grain size. Digestion was performed using the wet acid digestion method with a mixture of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$). The resulting filtrates were analyzed using Atomic Absorption Spectrophotometry (AAS) at specific wavelengths for Pb and Cu. Instrument calibration was conducted with certified standard solutions to ensure measurement accuracy.

Sediment Quality Guidelines

The obtained data were compared with the Canadian Sediment Quality Guidelines (CCME, 2002) and the Australian and New Zealand Sediment Quality Guidelines (ANZECC, 2000) (Table 1), since Indonesia has not yet established quality standards for heavy metals in sediments. This comparison was used to assess the level of heavy metal contamination risk in Palu Bay.

Table 1.
Comparative Quaity Standard

Quality Standard	Pb (mg/kg)	Cu (mg/kg)
CCME – ISQG	30.2	18.7
CCME – PEL	112	108
ANZECC – ISQG Low	50	65
ANZECC – ISQG High	220	270

Contamination Index

The contamination index (CI) was applied to assess the level of heavy metal pollution in sediments by comparing the measured concentrations with the geochemical background values. The background value (Cb) refers to the average shale value or nationally recognized standards. The calculation formula is as follows.

$$CF = \frac{CM\ sediment}{C\ background} \qquad (1)$$

where Cmetal is the concentration of the metal in the sediment sample (mg/kg), and Cbackground is the background value. A CF value < 1 indicates low contamination, 1–3 indicates moderate contamination, 3–6 indicates considerable contamination, and > 6 indicates very high contamination.

Geoaccumulation Index (Igeo)

The Geoaccumulation Index (Igeo) is used to assess the degree of heavy metal accumulation in sediments while taking into account a correction factor for possible variations in sediment composition. The formula proposed by Müller is as follows (Fadlillah et al., 2023).

$$Igeo = log2\left(\frac{\text{Cn}}{1{,}5\times(\text{Bn})}\right) \quad (2)$$

where Cn is the concentration of element *n* in the sediment sample, and Bn is the background concentration of heavy metal *n* in nature. The factor 1.5 is applied in the equation as a correction for background variation due to lithogenic effects. This factor also indicates minor anthropogenic influences on the sediment. The geoaccumulation index is divided into 7 classes from unpolluted to extremely polluted as shown in Table 2 (Fadlillah et al., 2023).

Table 2.
Classification of pollution level based on Igeo

Geoaccumulation index Igeo	Classification
Igeo ≤ 0	Unpolluted
0 < Igeo <1	Unpolluted to moderately polluted
1 < Igeo <2	Moderately polluted
2 < Igeo <3	Moderately polluted to heavily polluted
3 < Igeo <4	Heavily polluted
4 < Igeo <5	Heavily polluted to extreme polluted
Igeo >5	Extreme polluted

Human Health Risk Asseement

Human health risk was assessed followed U.S. EPA guidelines, considering dermal exposure to contaminated sediments. Oral ingestion pathways were not included because this study aimed to evaluate direct sediment contact exposure as an initial screening-level assessment. This limitation is acknowledged. Exposure parameters used in the HRA are summarized in Table 3 (Koki et al., 2015), . The chronic daily intake via dermal contact (CDI_dermal) was calculated, followed by hazard quotient (HQ) and hazard index (HI) estimation. Only Pb and Cu were included in the risk calculations. Carcinogenic risk (CR) was estimated for Pb using an oral slope factor adopted from the California Office of Environmental Health Hazard Assessment (OEHHA), as no official U.S. EPA oral slope factor for Pb is currently available. The use of this value is recognized as a methodological limitation.

Table 3.
Human health risk assessment input parameters for dermal exposure

Parameters	Value
Skin surface area (SA)	3300
Adherence factor (AF)	0.2
Dermal absorption factor (ABS)	0.001
Exposure frequency (EF)	350
Exposure duration (ED)	30
Body weight (BW)	70
Averaging time (AT)	10,950

Non-carcinogenic Risk

The hazard quotient (HQ) was calculated by dividing the chronic daily intake (CDI) of a metal, through dermal exposure, by its reference dose (RfD) to assess the human health risk (non-carcinogenic) contributed by individual metals in sediments. The RfD values used were adopted from (US EPA, 1989,2002; Abdelaal et al., 2024). The CDI dermal (mg/kg/ day) calculated as follows:

$$CDI\ dermal = \frac{Cs\ \times CF \times SA \times ABS \times EF \times ED}{BW \times AT} \quad (3)$$

where CS is a metal content (mg/kg) in sediments; CF is a conversion factor (kg/mg); SA is the exposed surface area of skin (cm2 /event); AF is the skin adherence factor (mg/cm2); ABS is the dermal absorption factor (unitless); EF is the exposure frequency (events/year); ED is the exposure duration (years); BW is the average body weight (kg); AT is the average time (days) (US EPA, 1989, 2002). The values of CDI dermal input parameters are given in. The HQ calculated as follow:

$$HQ = \frac{CDI}{RfD} \quad (4)$$

where the RfD (mg/kg/day) is the maximum daily exposure allowed dose for human. The RfD used values (mg/kg/day) of Pb and Cu are 0.003 and 0.037, respectively. Two classes describe HQ were listed in Table 1. The calculated hazard index (HI) assesses the likelihood that different metals in the investigated sediment will have negative health impacts. The HI calculated as the sum of HQ as follows:

$$HI = \sum_{i=l}^{n} HQi \quad (5)$$

Carcinogenic Risk

Carcinogenic risk (CR) is calculated based on lifetime exposure to each heavy metal and its corresponding cancer slope factor. The CR value is determined using the following formula (Eid et al., 2024) :

$$CRi = \sum_{i=l}^{n} CSFi\ \times CDIi \quad (6)$$

where CRi represents the carcinogenic risk for each metal, CDIi is the chronic daily intake of each metal, and CSFi is the cancer slope factor for the inorganic metal. The acceptable lifetime carcinogenic risk range is between 10-

6 and 10^{-4}. If the CR value exceeds 10^{-4}, there is a potential cancer risk for the population.

RESULT AND DISCUSSION

Heavy Metals In Sediment

Pb concentrations ranged from 2.17 to 13.80 mg/kg, with a mean value of 6.61 ± 3.64 mg/kg. Cu concentrations ranged from 5.02 to 37.67 mg/kg, with a mean of 20.70 ± 8.83 mg/kg (Table 4). All measured concentrations were below CCME and ANZECC guideline values.

Table 4.
Concentrations of Pb and Cu in surface sediments of Palu Bay

Station	Description area	Pb (mg/kg)	Cu (mg/kg)
1	Near Hotel	3.63	14.57
2	Near the mall	13.8	37.67
3	Near Hotel	7.31	24.35
4	Palu river estuary	7.11	23.43
5	Palu river estuary	7.9	27.09
6	Near Hotel	2.47	9.72
7	Pondo River Estuary	2.61	15.67
8	Near Salt Farm	6.33	15.91
9	Fishing village waters	2.17	5.02
10	Tondo River Estuary	6.78	28.59
Mean ± SD		6.01 ± 3.53	20.20 ± 9.78

Source: (Paundanan, 2025)

The concentrations of Pb and Cu in Palu Bay sediments showed clear spatial variation, as indicated by their respective ranges and standard deviations, reflecting heterogeneous anthropogenic influences across stations (Table 4). Stations located near urban areas, river estuaries, and commercial zones exhibited higher concentrations, particularly Station 2, which recorded the highest Pb and Cu levels. This pattern is consistent with previous studies reporting that coastal sediments near human activity centers tend to accumulate higher metal loads due to urban runoff, wastewater discharge, and maritime activities (Kuang et al., 2021; Li et al., 2021; Shi et al., 2024).

Despite this variability, the mean concentrations of Pb (6.01 mg/kg) and Cu (20.20 mg/kg) remained below international sediment quality guideline thresholds, suggesting limited overall contamination. Similar concentration ranges have been reported in Indonesian coastal environments with moderate anthropogenic pressure (Budiyanto & Lestari, 2017; Fadlillah et al., 2023; Ismanto et al., 2024). Therefore, the observed metal distribution indicates localized enrichment rather than widespread sediment contamination in Palu Bay (Khaled et al., 2017; Naik et al., 2023).

When compared to international sediment quality guidelines such as CCME (2002) and ANZECC/ARMCANZ (2000), Pb and Cu concentrations in Palu Bay sediments were well below the threshold effect levels. This indicates that the current contamination status is unlikely to pose immediate ecological risks to benthic organisms, consistent with findings from other coastal sediment studies with low metal loads (Putri et al., 2025; Sojka et al., 2023). However, Cu concentrations at certain stations approached guideline values, suggesting the need for localized attention. Long-term studies have demonstrated that continuous low-level metal inputs can gradually lead to sediment accumulation and ecological impairment (Tang et al., 2022). Coastal environments such as Palu Bay are particularly sensitive due to sediment trapping processes and semi-enclosed hydrodynamic conditions, highlighting the importance of preventive pollution control from land-based and shipping activities (Abdelaal et al., 2024).

Contamination Index

The contamination factor (CF) for Pb ranged between 0.11–0.69 with an average of 0.33, while Cu ranged from 0.11–0.84 with an average of 0.46. These values indicate a low level of contamination for both metals at all stations. Some locations, such as Station 2, showed relatively higher CF values compared to other sites, possibly reflecting anthropogenic inputs from human activities around the bay. In general, the sediments of Palu Bay are classified as uncontaminated according to CF values. The contamination factor (CF) analysis further supports the concentration data, with CF values for Pb and Cu consistently below 1 across all stations. Low CF values indicate that metal concentrations are close to natural background levels and reflect minimal anthropogenic contamination (Rongxi et al., 2020; Li et al., 2021).

Nevertheless, stations near river estuaries and urban infrastructure showed relatively higher CF values, suggesting site-specific anthropogenic inputs. Similar spatial trends have been reported in coastal areas influenced by combined land-based and maritime activities (Kuang et al., 2021; Shi et al., 2024). Pb exhibited slightly higher CF variability than Cu, likely due to its stronger affinity for fine sediment particles and organic matter. Overall, CF results classify Palu Bay sediments as uncontaminated but highlight zones that warrant closer monitoring.

The spatial distribution of CF values suggests different dominant pollution sources for Pb and Cu. Elevated Pb CF values near port and commercial areas are commonly associated with shipping activities, fuel combustion, and infrastructure runoff (Shi et al., 2024). In contrast, relatively higher Cu CF values near river mouths are often associated with domestic wastewater discharge and agricultural runoff transported from upstream catchments (Fadlillah et al., 2023; Tang et al., 2022). Such mixed-source contamination patterns are typical in rapidly developing tropical coastal regions (Rongxi et al., 2020). Although current CF values do not indicate moderate contamination, increasing coastal development may alter this condition, reinforcing the role of CF as an effective early-warning indicator (Li et al., 2021).

Geoaccumulation Index

The Igeo values for Pb ranged from –3.45 to –0.53 with an average of –1.59, while Cu values ranged from –3.49 to –0.41 with an average of –1.71. Based on the classification, these values fall into the unpolluted to moderately polluted category. Some sites with higher Igeo values are likely influenced by harbor activities and river discharges. The relatively low average values indicate that heavy metal pollution is not yet dominant in the area. However, the presence of certain hotspots still highlights the importance of continuous monitoring. The geoaccumulation index (Igeo) values for Pb and Cu were consistently negative, indicating uncontaminated to slightly contaminated sediment conditions according to Müller's classification. Negative Igeo values suggest that current metal concentrations are largely governed by natural background levels rather than historical anthropogenic accumulation (Muller, 1969; Zhang et al., 2020). These findings are consistent with studies in other tropical coastal systems experiencing moderate human pressure. The agreement between CF and Igeo results reinforces the conclusion that both recent and long-term metal enrichment in Palu Bay remains limited. However, stations with Igeo values approaching zero may represent early-stage accumulation zones. Continuous monitoring is therefore necessary to detect potential upward trends before critical thresholds are reached (Naik et al., 2023; Putri et al., 2025).

Using Igeo alongside CF provides a more comprehensive understanding of sediment contamination dynamics. While CF is sensitive to recent inputs, Igeo reflects cumulative historical deposition of metals in sediments (Zhang et al., 2020). In Palu Bay, the consistently low Igeo values indicate that sediment buffering capacity remains effective. Similar observations have been reported in bays with limited industrial activity but increasing urbanization (Tang et al., 2022)This combined approach enhances the reliability of sediment quality assessment and supports proactive environmental management. Consequently, Igeo can be applied as a long-term monitoring tool for Palu Bay sediment quality.

Non-carsinogenic Risk

The analysis of non-carcinogenic risks showed that the combined HI of Pb and Cu was 0.26, which is well below the threshold value of 1. The HQ value for Pb was 0.15 and for Cu was 0.11, both indicating no significant health risk. Differences among stations were relatively small, though local variations in exposure were observed. Stations with higher metal concentrations tended to have slightly elevated HQ values. Thus, the non-carcinogenic risk from heavy metals in Palu Bay sediments can be categorized as safe. The non-carcinogenic health risk assessment revealed that hazard quotients (HQ) for both Pb and Cu, as well as the combined hazard index (HI = 0.26), were well below the safety threshold of 1. This indicates that dermal exposure to these metals from Palu Bay sediments does not pose significant non-carcinogenic health risks under current conditions. Similar HI values below unity have been reported in coastal and estuarine environments with low sediment metal concentrations (Al-Kahtany et al., 2023; Shetty et al., 2024; Sojka et al., 2023).

Pb contributed more substantially to the overall HI than Cu, which can be attributed to its lower reference dose and higher inherent toxicity (Jaishankar et al., 2014; Yap & Al-Mutairi, 2022). Although spatial variation in HQ values was observed among stations, none approached levels of concern. These findings are consistent with previous sediment-based health risk assessments conducted in aquatic environments with comparable contamination levels (Enuneku & Ineh, 2020; Naik et al., 2023).

However, HI estimates are highly sensitive to exposure assumptions such as contact frequency, exposure duration, and skin adherence factors. Regulatory guidance recommends the use of conservative exposure parameters to avoid underestimation of health risks, particularly for vulnerable populations such as children (US EPA, 1989; Miletić et al., 2023). Moreover, health risk assessments based solely on sediment exposure may underestimate total risk, as bioaccumulation through seafood consumption was not considered. Numerous studies have demonstrated that metal concentrations in aquatic biota can exceed sediment levels and contribute significantly to human exposure (Huang et al., 2020; Tanjung et al., 2025). Therefore, integrating biota data into future risk assessments would enhance the public health relevance of the findings.

Carsinogenic Risk

Carcinogenic risk (CR) assessment was conducted only for Pb due to its more pronounced toxicological profile. The average CR value was 3,4 × 10^{-5}, which falls within the acceptable risk range defined by the US EPA 10^{-6}–10^{-4}). Some stations approached the upper limit, though still considered acceptable under regulatory standards. This finding suggests the presence of potential long-term risks, albeit relatively low. Therefore, routine monitoring remains necessary to prevent an increase in carcinogenic risks in the future. The carcinogenic risk (CR) assessment for Pb indicated values within the acceptable regulatory range of 10^{-6} to 10^{-4}, suggesting a negligible lifetime cancer risk from dermal exposure. The average CR value of 3.4 × 10^{-5} is comparable to those reported in other coastal sediment studies with low Pb concentrations (Eid et al., 2024; Khaled et al., 2017). The application of oral slope factors from the Office of Environmental Health Hazard Assessment is widely accepted in the absence of official USEPA slope factors for Pb (OEHHA, 2023).

Although CR values remained within acceptable limits, several stations approached the upper boundary of the recommended range, indicating potential long-term concerns. Environmental changes such as increased urban runoff or intensified maritime activities could elevate future exposure risks (Abdelaal et al., 2024; Shi et al., 2024). Furthermore, carcinogenic risk estimates are strongly influenced by exposure duration and ingestion assumptions, where minor parameter changes may significantly affect CR values (Shetty et al., 2024).

Additionally, indirect exposure pathways through the sediment–biota–human food chain were not evaluated in this study. Previous research has shown that seafood consumption can substantially increase Pb exposure, even when sediment-based CR values are low (Huang et al., 2020)(Tanjung et al., 2025) (Huang et al., 2020; Tanjung et al., 2025). Overall, current CR results indicate a stable and low-risk condition in Palu Bay; however, proactive environmental management and long-term monitoring are essential to maintain environmental and public health protection.

CONCLUSIONS

This study demonstrates that concentrations of lead (Pb) and copper (Cu) in surface sediments of Palu Bay are below international sediment quality guidelines (CCME and ANZECC), with contamination factor (CF<1) and negative geoaccumulation index (Igeo) values indicating low contamination levels. The human health risk assessment, conducted as a screening-level evaluation focusing on dermal exposure, showed that hazard quotients (HQ) and the combined hazard index (HI) were well below the threshold of concern (HI < 1), while the estimated carcinogenic risk (CR) for Pb remained within the acceptable range (10^{-6}–10^{-4}). These findings suggest that Pb and Cu in Palu Bay sediments currently pose minimal human health risk through dermal contact; however, observed spatial variations among stations underscore the importance of continuous monitoring to support long-term environmental management and sustainable coastal development.

SUGGESTION

Future research should expand the scope of heavy metal assessment by including additional toxic elements such as Hg, Cd, As, Cr, and Ni to obtain a more comprehensive understanding of contamination dynamics in Palu Bay. Further studies are also encouraged to investigate bioaccumulation in marine organisms, particularly benthic fish, mollusks, and crustaceans, to better evaluate human exposure through seafood consumption. Seasonal monitoring is recommended to capture temporal variations influenced by river discharge, rainfall patterns, and coastal activities. Incorporating physicochemical characteristics of sediments such as pH, organic matter content, grain size, and redox conditions will help clarify the mechanisms governing metal binding and remobilization.

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