SCIENTIFIC COMMITTEE
TWENTY-SECOND REGULAR SESSION
11 – 19 August 2026
Apia, Samoa

Methylmercury and other pollutants studies in tunas

WCPFC-SC22-2026-RP-P35b-03
11 July 2026

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Executive summary

- Tunas and billfishes are important seafood species but can accumulate contaminants such as mercury (Hg), methylmercury (MeHg), persistent organic pollutants (POPs), and plastics through marine food webs.
- Using samples from the WCPFC Pacific Marine Specimen Bank (PMSB) and other oceans, we assembled the largest global mercury database for tropical tunas and albacore and assessed contaminant risks and benefits for consumers.
- Species contamination levels differed: Skipjack and yellowfin generally had lower Hg concentrations than albacore, bigeye, swordfish, and marlins. Levels in some larger sampled bigeye individuals, in very few large albacore and yellowfin and in some billfish species were above FAO/WHO guidelines for predatory fish; those in all skipjack, in the vast majority of yellowfin and albacore sampled were lower (but not zero).
- Mercury concentrations varied geographically:
  - Yellowfin, bigeye, and albacore showed higher Hg levels around New Caledonia and Fiji than near the equator.
  - Skipjack Hg concentrations were 1.5–2 times higher in the northwestern Pacific than in the eastern Pacific, and 4–5 times higher than in the western-central Pacific.
  - Spatial Hg patterns were primarily driven by foraging depth and regional marine biogeochemistry controlling MeHg availability.
- Temporal trends revealed contrasting patterns:
  - Tuna Hg concentrations increased in the northwestern Pacific during the late 1990s, coinciding with rising Asian region Hg emissions.
  - Elsewhere, Hg levels remained stable despite declining emissions, reflecting the persistence of legacy mercury in the ocean.
- MeHg represented 70–100% of total Hg in tunas, swordfish, and striped marlin, but only ~15% in blue and black marlins, suggesting species-specific detoxification mechanisms and the need for tailored dietary advice.
- POPs and plastics were detected in skipjack and yellowfin from New Caledonia and PNG:
  - Contamination levels in muscle were low and currently pose no known health risk.
  - Plastic fragments or fibres were found in 30% of stomachs examined, and some plastic additives were detected in tuna tissues.
- Nutritional benefits remain high, within the 2 species tested: skipjack and yellowfin providing valuable fatty acids, including health-promoting omega-3s.
- Overall, tropical tunas and albacore are effective biomonitors of marine contamination, supporting the development of contaminant baselines and highlighting the need for large-scale monitoring programs to evaluate pollution trends, inform the human health implications, and the effectiveness of environmental policies. Funding is being sought for the work.

The scientific committee is invited to:

- Note the interest of conducting monitoring of pollutants in tuna and bycatch species that could potentially impact human health.
- Note the variations observed in pollutant concentrations according to fish species, size and catch location.
- Note the uncertainties existing on mercury contamination understanding and the capabilities for some species to detoxify, likely in relation to selenium.
- Note that tuna and bycatch species provide fatty acids and essential elements beneficial to human health.
- Support the ongoing activities of the Pacific Marine Specimen Bank to maintain an accessible repository of biological samples for long-term monitoring of known and emerging pollutants, thereby enhancing scientific understanding and informing evidence-based policies on the health risks and benefits of consuming tuna and bycatch species.

1. Background

Top predator fishes, in particular tunas, are among the most widely eaten saltwater fishes in the world, yet they are known to contain methylmercury (MeHg), the most toxic form of mercury (Hg). MeHg exposure is associated with neurocognitive deficits in children, and with cardiovascular effects in adults (Axelrad et al., 2007; Genchi et al., 2017), and its health and socioeconomic costs are estimated at one billion dollars annually worldwide (Zhang et al., 2021). The United Nations Environment Programme Minamata Convention aims at reducing anthropogenic Hg emissions to protect human health, advocating governments and policy makers to balance economic, environmental and health interests.

Mercury sources are both natural (e.g., volcanism, soil leaching) and anthropogenic (e.g., fossil fuel combustion and artisanal and small-scale gold mining) (Outridge et al., 2018), but their relative contributions are still poorly known. Once released, inorganic Hg transport and fate is complex and influenced by chemical, physical, biological and ecological processes. From the atmosphere, inorganic Hg can be deposited or taken up by the ocean, an unknown fraction of Hg is microbially converted into MeHg (Mason and Fitzgerald, 1990), which is easily absorbed by organisms and can biomagnify along marine food webs. This compound also bioaccumulates within individuals over time, resulting in higher MeHg concentrations in bigger fish. Humans are exposed to MeHg mainly by consuming marine fish (Sunderland et al., 2009), especially top predators such as tropical tunas and billfishes that exhibit high Hg concentrations compared to the rest of the food web (Bodin et al., 2017; Choy et al., 2009), sometimes exceeding food safety guidelines (1 mg/kg fresh tissue) (FAO/WHO, 2011). Understanding the factors that drive MeHg concentrations in top predator fishes, and how the implementation of Hg emission reduction measures change levels in fish, is therefore critical to policy makers and, ultimately, to limiting human exposure to MeHg.

In addition to mercury, there is increasing concern about emerging contaminants such as plastics and POPs (persistent organic pollutants). POPs are characterised by their low degradability in the environment, their accumulation in organisms and throughout food webs, and their toxicity. Furthermore, POPs are transported by the atmosphere and ocean currents far from their sources of emission. They are therefore found everywhere across the globe, although their production and use have been predominantly in the Northern Hemisphere. POPs include polychlorinated biphenyls (PCBs) used in industry, organochlorine pesticides (OCPs) such as DDT, brominated compounds (PBDEs) and per- and polyfluoroalkyl substances (PFAS). The vast majority of these POPs are now regulated, but because of the quantities used in the past and their persistence, they will remain in our environment for several decades to come.

Furthermore, plastics have become widespread in all the oceans due to their increasing use by human populations and the poor management of this waste. Plastic waste in the oceans consists of macro-debris (e.g. bottles, bags, nets) and micro-fragments with a diameter of less than 5 mm, known as microplastics. The latter result from the fragmentation of macro-debris already present in the sea and from accidental discharges (industrial abrasives, cosmetics, etc.). Furthermore, additives are incorporated during the manufacture of plastics to give them specific properties (heat resistance, colouring agents). These additives can account for more than half the total weight of certain plastics, and some of them may be released into the environment. The most commonly used additives, such as phthalates and bisphenol A, are recognised as being toxic. Furthermore, microplastics act as carriers for the adsorption of POPs already present in the environment. Due to their ubiquitous presence and small size, microplastics can be ingested by marine organisms and release their additives and pollutants during digestion, potentially causing toxic effects and posing a risk to consumers.

This paper summarizes the results of a recent project (2021-2023) aiming at obtaining baseline values of plastic and POPs contamination in the western Pacific as well as 11 years of research (2014-2025) conducted in the Pacific primarily and extended to other oceans on mercury. Our work has focused mainly on tropical tunas and albacore, i.e., top predator species that are distributed and highly exploited globally, assessing spatial and temporal patterns of tuna MeHg concentrations with the aim of tackling the yet-unanswered question of what controls the origin and fate of MeHg in tunas in the global ocean. To further evaluate the risks of MeHg exposure associated to top predatory fish consumption, we extended our research to billfishes, characterizing total Hg and MeHg concentrations in fish muscle to explore species-specific Hg metabolic pathways and their implications for food safety monitoring.

2. Material and methods

With the help of multiple partners, including the Pacific Community, and assisted by access to several tuna tissue banks including the WCPFC Pacific Marine Specimen Bank, we compiled more than 5,700 total Hg concentrations measured in muscle tissue of tropical tunas (n = 1,422 bigeye, 2,467 yellowfin, and 1,003 skipjack) and albacore (n = 900) from the Pacific (n = 3,551), Indian (n = 1,218) and Atlantic (n = 1,023) oceans. Specific sampling protocols were implemented in New Caledonia and Papua New Guinea to collect 20 stomachs and muscles for plastic and plastic's additives analyses (n=10 yellowfin and 10 skipjack) and 81 fish for POPs analyses (n=39 yellowfin and 42 skipjack) . We complemented the Hg global tuna database with Hg measurements in four billfish species (i.e., swordfish, striped marlin, blue marlin, and black marlin) from the Pacific and the Indian Ocean. The vast majority of total Hg and MeHg analyses was performed at GET (Toulouse, France).

Analyses of POPs were conducted at IFREMER/CCEM laboratory (France), analyses of plastic in stomachs at the SPC FAME laboratory (New Caledonia) and Sorbonne University METIS laboratory (France), and analyses of plastic additives in muscle tissue were performed at Labocea (France). For each tuna and billfish sample, precise date and coordinates of fishing operations were recorded to be able to explore spatial and temporal variability of contaminant concentrations at a high resolution. Individual tuna length was also recorded to account for natural bioaccumulation of Hg over time. See Médieu (2022) for additional information on fishes sampling and Hg chemical analyses.

3. Tunas help to map mercury bioavailability and pollution in the ocean

Despite the scientific interest, and the public health and economic needs to document tuna Hg variability in the global ocean, the vast majority of studies available to date have been conducted on a small spatial scale, relying most of the time on imprecise tuna catch locations. Intra-specific differences of tuna Hg levels were highlighted regionally in the eastern Pacific (Ferriss and Essington, 2011) and the western Indian (Chouvelon et al., 2017), and among 12 locations in the global ocean (Nicklisch et al., 2017), yet relying on spot samples acquired at a low spatial resolution, and without identifying the drivers.

Our global dataset enabled the production of broad-scale and high-resolution maps of Hg concentrations in bigeye, yellowfin, and albacore in the western central Pacific region (Houssard et al., 2019), and in skipjack in the entire Pacific Ocean (Médieu et al., 2022). Within the western central Pacific region, higher standardized Hg levels were found around New Caledonia and Fiji compared to the equator, in yellowfin, bigeye and albacore (Fig. 1A-C) (Houssard et al., 2019). In skipjack, standardized Hg concentrations were 1.5 to 2.0 times higher in the northwestern Pacific than in the eastern region, and 4.0 to 5.0 times higher than in the western central Pacific (Fig. 1D) (Médieu et al., 2022).

Using a set of tracers, we showed that most of this spatial variability was explained by the combination between tuna foraging depth and the natural biogeochemical functioning of the ocean, in particular the depth at which MeHg concentrations peak in the water column (Houssard et al., 2019; Médieu et al., 2022). Around New Caledonia and Fiji, we illustrated this link between MeHg levels in seawater and tunas using MeHg concentrations measured from the surface down to 600 m during the 2015 OUTPACE sea campaign (Leblanc and Cornet, 2018) and Hg concentrations in muscle and blood samples of tropical tunas and albacore, four species known to exhibit contrasted foraging depths in the western Pacific according to tagging data (Evans et al., 2011; Houssard et al., 2017; Williams et al., 2015). Such comparison revealed a significant positive trend between dissolved MeHg concentrations and tunas Hg levels (Fig. 2), confirming the importance of both marine biogeochemical processes leading to variable MeHg levels in seawater, and tuna foraging depth (Barbosa et al., 2022). Yet, the relatively high skipjack Hg levels in the northwest Pacific (Fig. 1D) may also be due to major sources of anthropogenic Hg releases nearby, associated with the use of fossil fuels for power generation in Asia (Médieu et al., 2022). Such human-related sources add to natural biogeochemical processes that are conducive to surface MeHg bioavailability in food webs.

Overall, these broad-scale and transdisciplinary studies lead to the hypothesis that the spatial variability in tuna Hg concentrations is mainly explained by both tuna foraging depth and the vertical and horizontal variability of MeHg bioavailability in the ocean. These results shed light on the potential power of combining tropical tunas and albacore to investigate both horizontal and vertical variability of MeHg bioavailability in the water column, and MeHg biomagnification pathways along pelagic food webs.

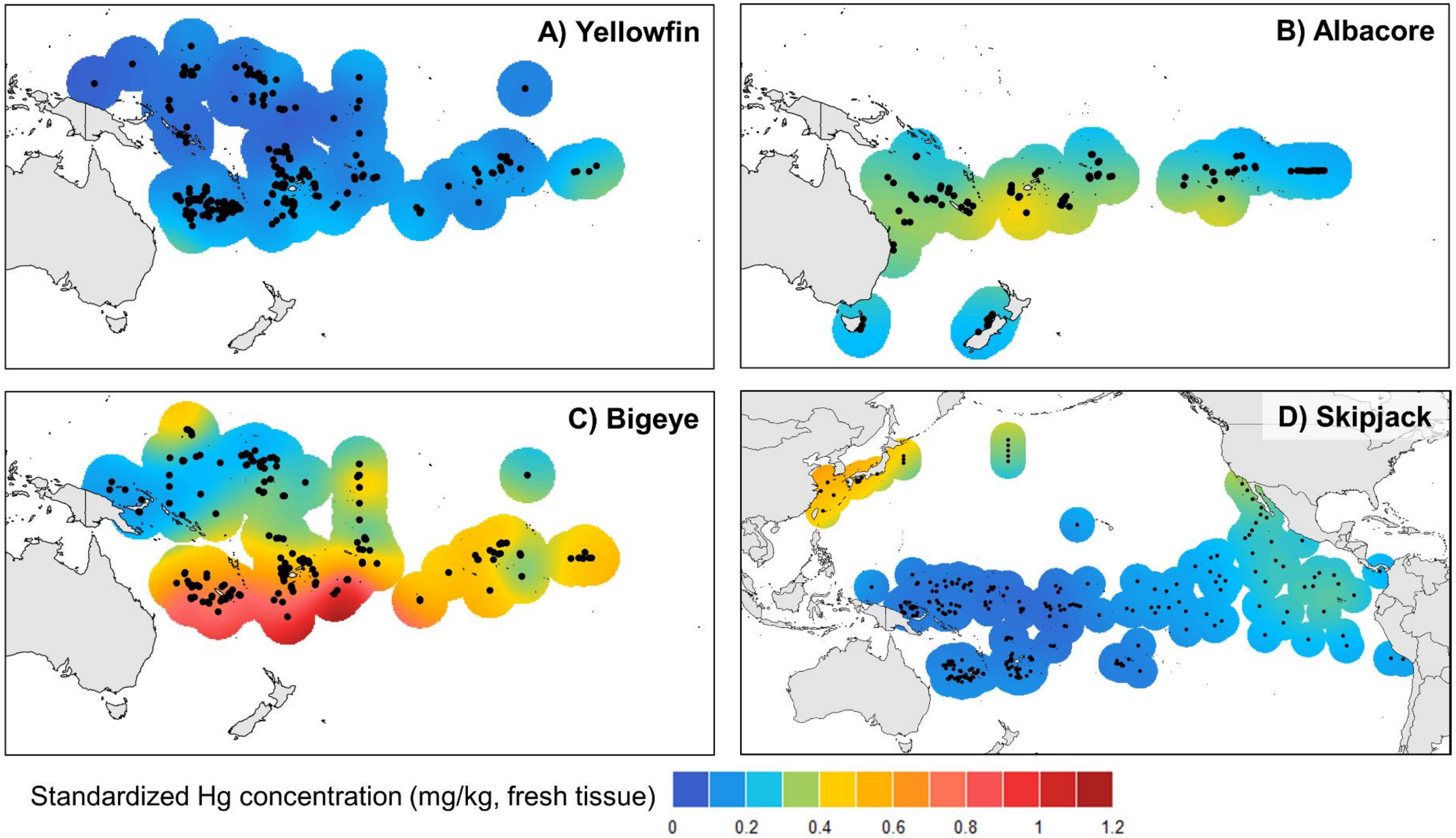

Figure 1. Spatial distribution of standardized mercury concentrations (Hg, mg/kg, fresh tissue) in **A)** yellowfin, **B)** albacore, **C)** bigeye, and **D)** skipjack, from Houssard et al., (2019) and Médieu et al., (2022). Black dots show the catch location of the sampled fish.

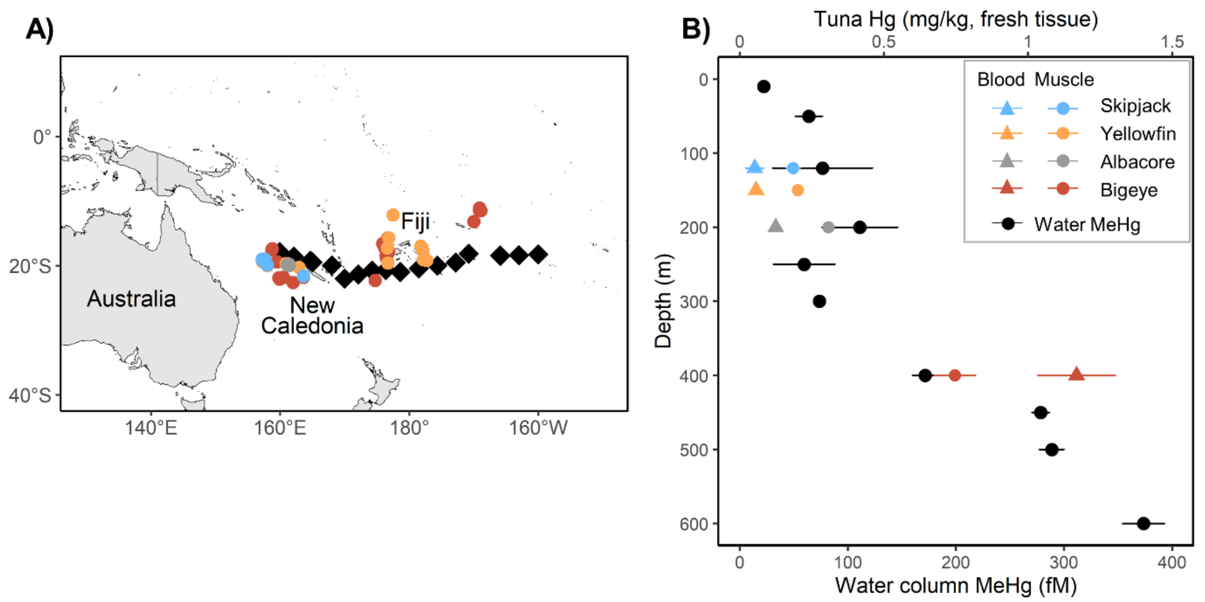

Figure 2. The importance of tuna foraging depth in the context of marine methylmercury (MeHg) depth profiles in the southwestern Pacific Ocean. **A)** Location of seawater (black diamonds) and tuna (colored dots) blood and muscle samples used to investigate the link between tuna mercury (Hg) concentrations and dissolved MeHg levels in the water. **B)** Relationship between total Hg concentrations (mg/kg, fresh tissue) in tuna species exhibiting different foraging depths, and concentration-depth profile of dissolved MeHg (femtomolar fM, concentration-depth profiles were averaged from all locations), from Barbosa et al. (2022). Species-specific foraging depths were estimated with tagging data from the western Pacific Ocean (Evans et al., 2011; Houssard et al., 2017; Williams et al., 2015).

4. Stable mercury concentrations in tuna since 1971 illustrate marine inertia and the need for strong emissions reductions

Another key question regarding the marine Hg cycle is whether Hg trends in marine biota can reflect temporal changes of anthropogenic Hg releases into the atmosphere initiated through the UNEP Minamata Convention. To tackle this question, we provided the longest time series of tuna Hg concentrations ever compiled at a global scale (Fig. 3A; Médieu et al., 2024) and compared them to estimated regional anthropogenic Hg emissions to the atmosphere since the 1970s (Fig. 3B; Streets et al., 2019a, 2019b). We pointed out that, although highly variable, these concentrations remained stable between 1971 and 2022, except in the northwest Pacific where they increased significantly 4-fold in the late 1990s (Fig. 3C). This increase likely reflects the concomitant anthropogenic Hg release from Asia. Elsewhere in the global ocean, the stability of tuna Hg levels contrasts with decreasing global anthropogenic releases and is thought to be related to the ocean inertia. This highlights the accumulation of Hg released several decades and centuries ago, which continues to flow into the ocean waters where tuna live. Using a Hg circulation model (Amos et al., 2013), we illustrated that even if Hg emissions were drastically reduced, it would require between 10-25 years to detect a decline in tuna Hg levels. These results call for more aggressive emission reduction measures globally. Furthermore, our global database of tuna Hg levels has been accredited by the Convention and is currently being used in its first effectiveness evaluation. This highlights the need for continuous and long-term global monitoring of Hg levels in tunas to explore future trends of tuna Hg levels and explore the marine Hg cycle in the context of climate change and changing anthropogenic Hg releases to the environment. Such monitoring has been carried out since 2001 in the western Pacific thanks to the Pacific Marine Specimen Bank, which enables many tuna samples to be collected yearly by onboard fisheries observers, and that can be laboratory-tested for Hg.

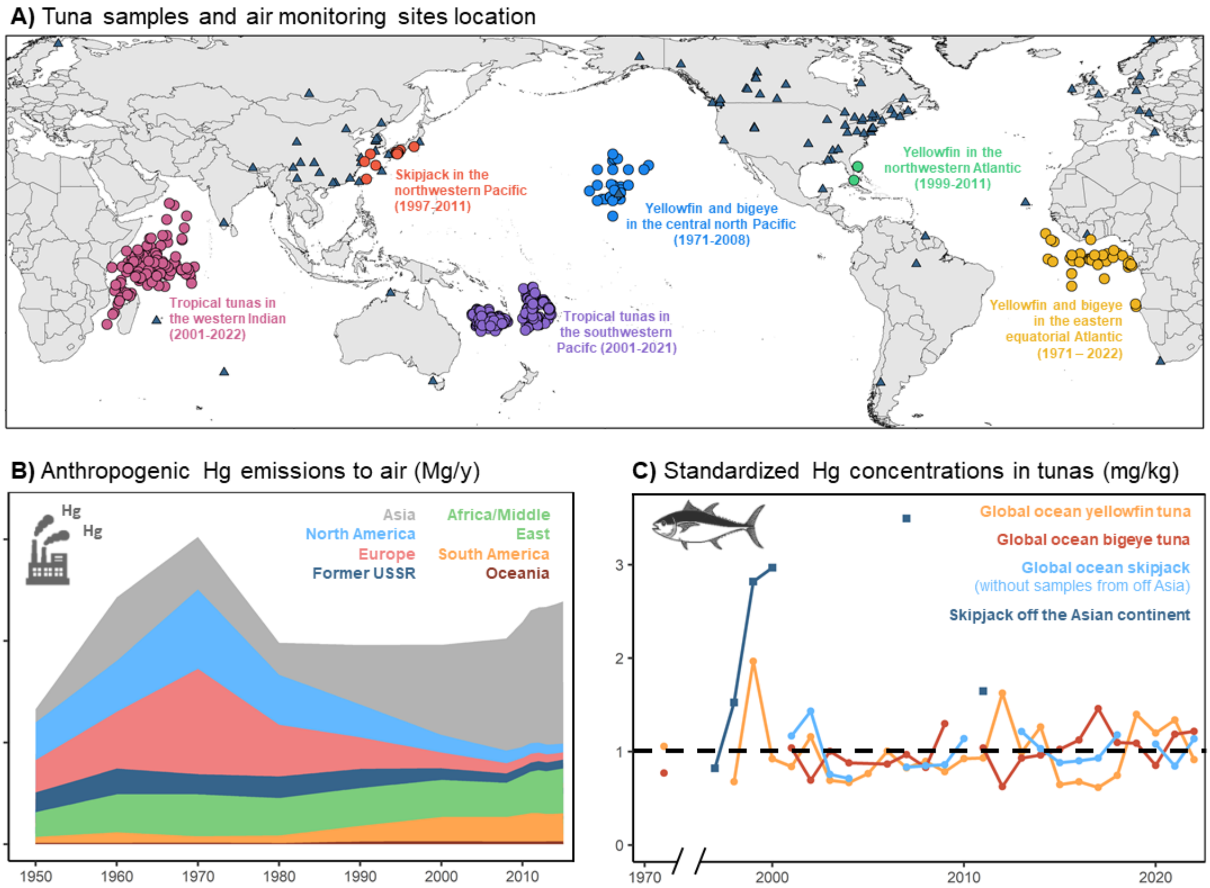

Figure 3. A) Spatial distribution of tropical tunas analysed for mercury (coloured circles) and atmospheric mercury level observation sites (blue triangles). **B)** Temporal anthropogenic mercury releases from 1950 to 2010 by world region, from Streets et al. (2019a, 2019b). **C)** Temporal variability of mercury concentrations (Hg, mg/g) in tropical tunas: yellowfin (orange), bigeye (red), and skipjack (blue), from Médieu et al. (2024). The colored dots represent average annual concentrations measured in the global ocean, except in the northwestern Pacific, off Asia. In that area, average annual concentrations are represented by dark blue squares.

5. Inter-species differences in Hg metabolism and their implications for food safety guidelines

In addition to serving as biomonitoring tools of the global Hg cycle, measurements of Hg concentrations in marine top predators provide valuable information for assessing human exposure to Hg through the consumption of these species. To limit risks on human health of MeHg exposure, consumption guideline levels for MeHg were set at 1 mg/kg (fresh tissue) for predatory fishes such as tunas and billfishes, and 0.5 or 0.3 $\mu g.g^{-1}$ for other species (FAO/WHO, 2011), depending on the country. We relate identified levels in tuna to both guidelines. Across the investigated tuna species, Hg concentrations generally follow the general pattern in the global ocean: bigeye > albacore > yellowfin and skipjack (Médieu et al., 2023), as observed in tunas caught off New Caledonia (Fig. 4). In this region, all skipjack samples analyzed were < 0.5 mg/kg, and 4 % were > 0.3 mg/kg, the strictest food safety guideline. About 8 % and 2 % of the yellowfin samples were > 0.3 and > 0.5 mg/kg, respectively. Similarly, 3 % and 37 % of albacore tuna were > 0.3 and > 0.5 mg/kg, respectively. Bigeye displayed the highest Hg concentration among the tuna group, most of them (92 %) > 0.3, and 33 % of them > 1 mg/kg, the food safety guideline used for predatory fishes (FAO and WHO, 2005), skipjack samples always show Hg levels below the limit. Samples with Hg concentrations exceeding the limits are generally associated with bigger individuals, illustrating the natural bioaccumulation of Hg in organisms through time, and the consequent need to consider both tuna species and fish size when addressing recommendations of food safety regarding Hg content.

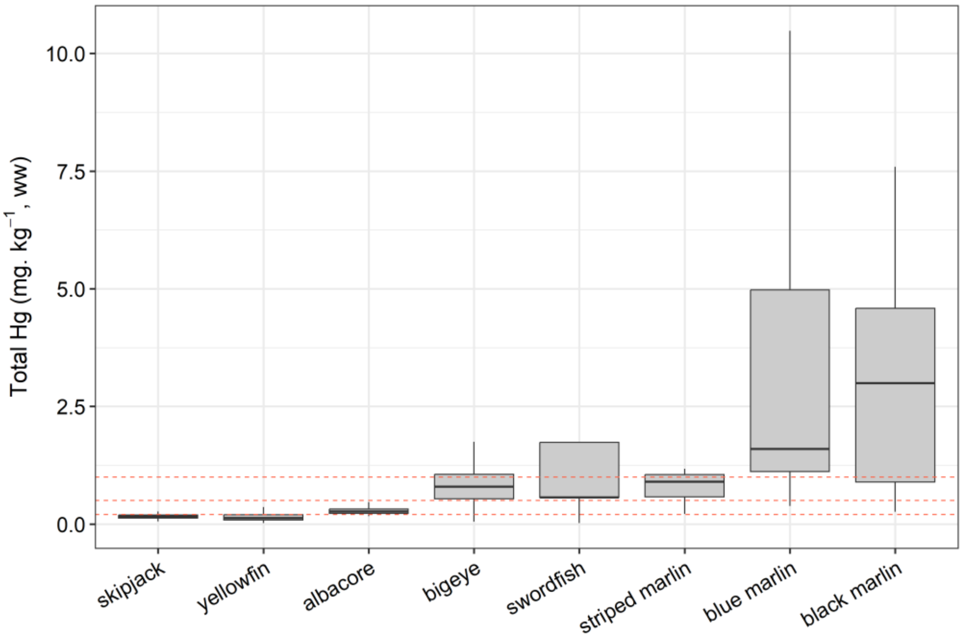

Figure 4. Total mercury concentrations (Hg, mg/kg fresh tissue) measured in tunas and billfishes from New Caledonia. The dashed red lines represent the food safety guidelines of 0.3, 0.5, and 1 mg/kg, respectively.

While consumption guidelines are defined regarding fish MeHg content, risk assessments are generally based on total Hg concentrations, assuming that most Hg is usually in its organic form in fish muscle tissue. Indeed MeHg represents between 70 and 100 % of total Hg in the muscle of tropical tunas and albacore (Médieu et al., 2023); yet, low MeHg proportions were recently reported in marlins, suggesting more complex Hg metabolism across predatory fishes. We measured total Hg and MeHg concentrations in muscle tissue of four billfish species – swordfish (*Xiphias gladius*), striped marlin (*Kajikia audax*), blue marlin (*Makaira nigricans*), and black marlin (*M. indica*) - from New Caledonia and three locations in the Indian Ocean to address this knowledge gap (Médieu et al., 2025). We found that MeHg is the dominant (~90 %) Hg compound in swordfish and striped marlin, but represents only a small portion (<15 %) in blue and black marlins, suggesting the existence of *in vivo* MeHg detoxification capabilities in these last two species (Fig. 5). By revealing species-specific MeHg biomagnification patterns, we showed that children and adults can eat more frequently blue and black marlins than swordfish and marlins. These findings highlight the need to adapt dietary advice to each billfish species, instead of considering them as a single fish category, as commonly done by health agencies, and to measure MeHg, rather than total Hg, to better assess the potential risks for human health.

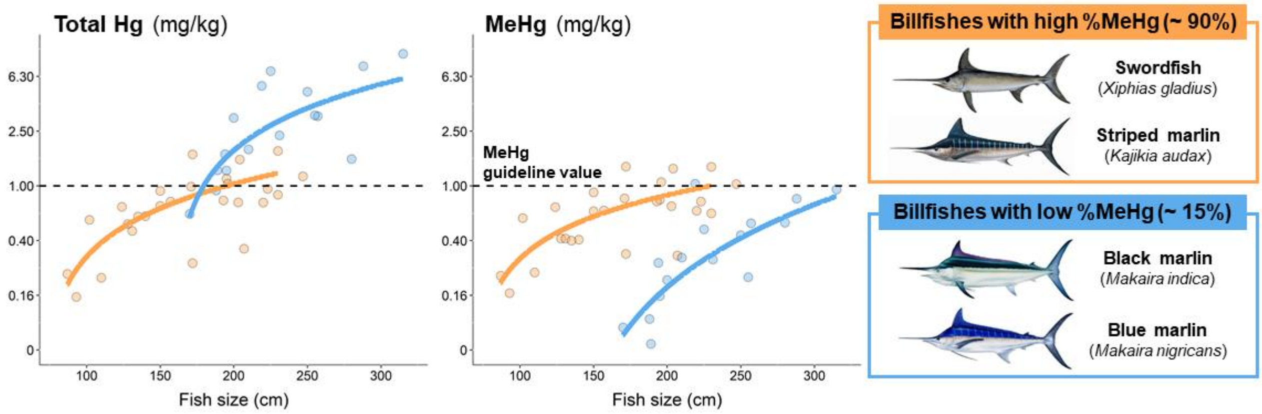

Figure 5. Total mercury (Hg, left) and methylmercury (MeHg, center) concentrations in four billfish species, highlighting species-specific *in vivo* detoxification of MeHg in blue and black marlins, from Médieu et al., (2025). The dashed line represents the consumption level guideline for MeHg set at 1 mg/kg fresh tissue (FAO/WHO, 2011).

In addition, the combined investigation of total selenium (Se) concentrations revealed a strong and positive correlation between low MeHg proportions and Se levels exclusively in blue and black marlins. This suggests the involvement of Se-dependent *in vivo* detoxification mechanisms for MeHg, with inert and poorly bioavailable Hg-selenide (HgSe) nanoparticles likely being the final product (Manceau et al., 2021a). Recent analytical developments have enabled the documentation of such Se-dependant mechanisms in the liver and kidneys of seabirds and marine mammals (Manceau et al., 2021b, 2021c), and in the spleen of Atlantic bluefin tuna (Wiech et al., 2024).

Among the various chemical forms of Se, selenoneine, a newly discovered Se compound (Yamashita and Yamashita, 2010), is raising particular interest because it is highly abundant in the muscle of marine fishes, especially tunas and swordfish (Seko et al., 2025). It exhibits a strong antioxidant capacity and a high affinity for Hg, and promotes MeHg demethylation in seabirds and marine mammals (El Hanafi et al., 2022; Yamashita et al., 2013). Emerging data now suggest that selenoneine is a key molecular precursor to MeHg detoxification in marine predatory fishes such as tunas and marlins (Manceau et al., 2025), and potentially in humans, although the underlying mechanisms remain incompletely understood. Current investigation exploring different chemical forms of Hg and Se chemical forms, in particular MeHg and selenoneine, in a diversity of tissues of tropical tunas, albacore, swordfish and marlins is being performed by our team to explore internal Hg-Se interactions in these predatory fishes and better understand the mechanisms driving species-specific differences of MeHg detoxification.

6. Plastics and persistent organic pollutants accumulation in tunas

Around a hundred PMSB samples were used to carry out a study on the contamination of skipjack and yellowfin tuna in New Caledonia and Papua New Guinea. The project's objectives were to provide knowledge on the bioaccumulation of persistent organic pollutants (POPs) such as pesticides, and on the presence of mercury, plastics and plastic additives in tuna from the south-west Pacific. The results will help to assess human exposure to these contaminants through seafood consumption. The results show:

- Tuna contamination by POPs exists in New Caledonia and Papua New Guinea, which is part of the global distribution of POPs, even in areas far from sources of pollution in the northern hemisphere (Fig. 6).
- Levels of POP contamination in tuna remain low compared to values in other oceans (Munschy et al. 2020), and consumption of these fish currently poses no health risk in relation to these substances.
- The stomachs of 6 out of 20 tuna contained plastic fragments or fibres >2mm, and these synthetic materials were mainly polypropylene and polyester (Fig. 7).
- Two plastic additives in particular have been detected in tuna, at levels comparable to those found in Spain (Sambolino et al., 2023). There are no health standards for these substances.
- Consumption of the two species of tuna in the two areas provides a wide range of fatty acids, including omega-3, which are beneficial to health (Fig. 8).

Even if current levels of contaminants measured are relatively low for components for which standards exist (POPs), it is important to remain vigilant in order to preserve these marine resources, which are essential from both an ecological and socio-economic point of view, in the context of global change and the impact of increasing human activities. In addition, food safety guidelines have yet to be established for many compounds such as plastic additives. Finally, we have confirmed that skipjack and yellowfin tuna remain important sources of fatty acids, particularly omega-3, which are beneficial to human health.

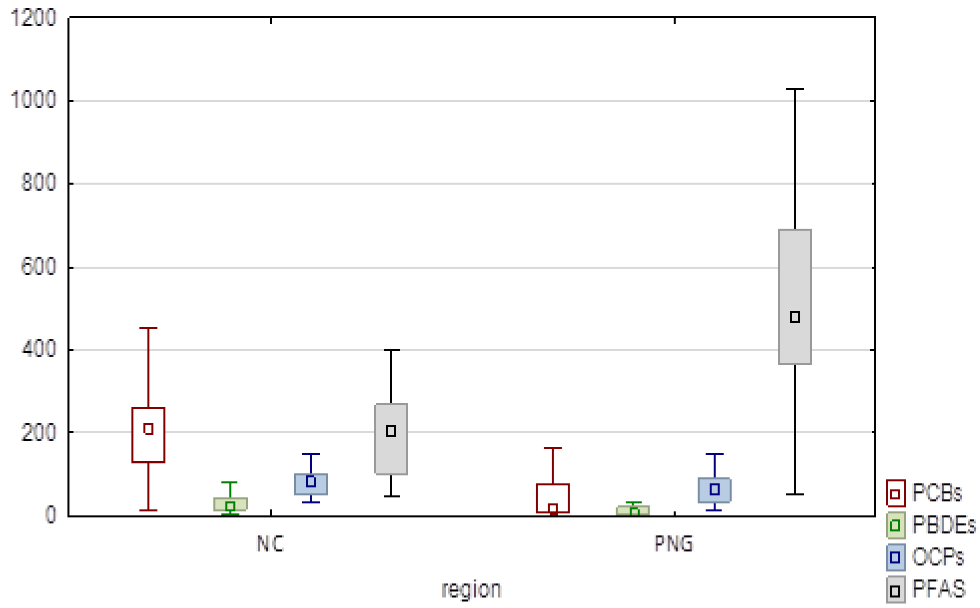

Figure 6. Concentrations (pg g^{-1} fresh tissue) of the major families of persistent organic pollutants in tropical tuna collected in New Caledonia (NC) and Papua New Guinea (PNG) in 2020–2021.

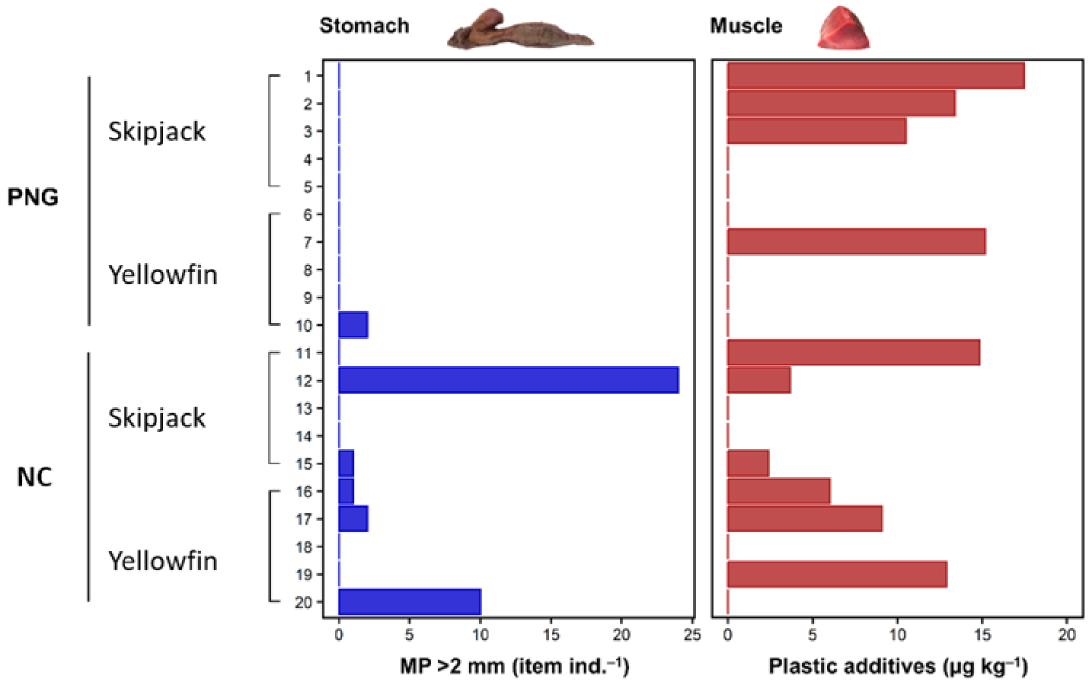

Figure 7. Contamination of plastic particles >2mm in the stomachs (blue) and plastic additives in the muscle of 20 specimens of 2 species of tuna (skipjack and yellowfin tuna) in New Caledonia (NC) and Papua New Guinea (PNG).

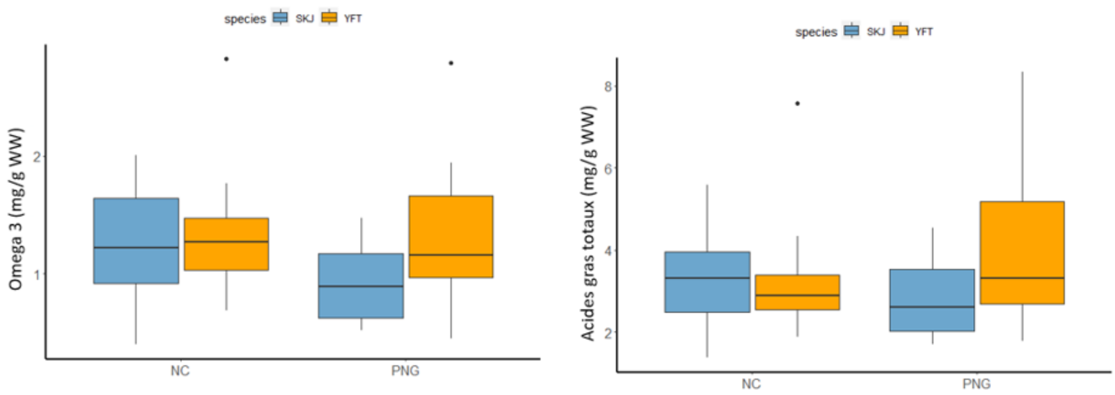

Figure 8. Omega 3 and total fatty acid concentrations in mg/g fresh tissue for skipjack (SKJ) and yellowfin tuna (YFT) from New Caledonia (NC) and Papua New Guinea (PNG).

7. Implications for the global mercury cycle and food safety monitoring

This work has highlighted that tropical tunas and albacore as effective bioindicator species for ocean Hg contamination, as they appear to reflect a given ecosystem's Hg exposure while also including several Hg sources on various spatial and temporal scales. Combined with Hg measurements in the air and the ocean, tunas provide vital information for evaluating large-scale Hg environmental policies under the Minamata Convention. This calls for continuous and long-term global monitoring of tuna Hg to explore future trends of Hg levels in tunas and to explore the marine Hg cycle in the context of rapid climate change and changing anthropogenic Hg releases to the environment. Such monitoring has been carried out since 2001 in the western Pacific thanks to the Pacific Marine Specimen Bank, which enable many tuna samples to be collected yearly by onboard fisheries observers and port samplers, and that can be laboratory-tested for Hg. An exploratory study was conducted on plastics and POPs in the region already demonstrating spatial variability and establishing a baseline and monitoring programme of those contaminants at the regional level would allow understanding to be gained on the contaminants' cycle and evolution.

Continuous contaminant monitoring in tunas and billfishes remains essential for assessing human exposure to MeHg and other contaminants through the consumption of these species. Building on our ongoing research and expertise, a key priority is to better understand the interactions between Hg and Se, particularly the extent to which Se may mitigate MeHg toxicity in both marine organisms and humans. Improving our understanding of these mechanisms is critical to protect against MeHg toxicity while ensuring the nutritional benefits associated to the consumption of these marine fishes. Such knowledge has particular importance for Pacific Island countries and territories, where tunas and billfishes are central to culture, nutrition, and local economies. Nutritional studies that document Hg and Se exposure levels in consumers, combined with socio-economics studies exploring consumers' perceptions and behaviours, would provide valuable information to health agencies to ultimately adjust food safety recommendations that ensure access to safe and nutritious seafood while supporting sustainable blue economies and food security in the Pacific region.

Funding is being sought to continue this specialised work within the Pacific region.

8. Recommendations

The scientific committee is invited to:

- Note the interest of conducting monitoring of pollutants in tuna and bycatch species that could potentially impact human health.
- Note the variations observed in pollutant concentrations according to fish species,size and catch location.
- Note the uncertainties existing on mercury contamination understanding and the capabilities for some species to detoxify, likely in relation to selenium
- Note that tuna and bycatch species provide fatty acids and essential elements beneficial to human health
- Support the ongoing activities of the Pacific Marine Specimen Bank to maintain an accessible repository of biological samples for long-term monitoring of known and emerging pollutants, thereby enhancing scientific understanding and informing evidence-based policies on the health risks and benefits of consuming tuna and bycatch species.

9. Acknowledgements:

Generative AI tools [Microsoft Copilot] were used to assist with editing some text in this document. All analytical choices, model specifications, diagnostic interpretations, and conclusions are those of the authors, who reviewed and verified all AI-assisted output. The methodology, model implementation, and the scientific conclusions are the responsibility of the authors.

This work has been conducted in the framework and with the financial support of the Pacific Fund VACOPA project (spatial VAriations of COntaminants levels in the PAcific ocean trophic webs; 2014-2017), ANR-17-CE34-0010 MERTOX (unravelling the origin of methylMERcury TOXin in marine ecosystems, 2017-2022) from the French Agence Nationale de la Recherche, the Pacific Fund TIPTOP project (project n°2014; 2020-2023), IRD and GEF. It will continue through the IMPACT project (Mercury-selenium interactions in tunas, risks and benefits of their consumption, and consumer motivations and sensitivity; 2026-2029) from France Filière Pêche. It also benefited from financial support from Région Bretagne and Université de Bretagne Occidentale (UBO), and was assisted by collaborations under the international framework of the IMBeR regional program Climate Impacts On Oceanic Top Predators (CLIOTOP). We are grateful to the research communities working on tuna ecology, mercury cycle, biogeochemical modelling, and toxicology who contributed to this research. We also thank all the fishermen, observers, port samplers, and technical staff who participated in the collection and preparation of tuna samples. In particular, we are grateful to the WCPFC Pacific Marine Specimen Bank and the Pacific Community (SPC) Fisheries, Aquaculture and Marine Ecosystems (FAME) division for collating and providing tuna and billfish tissue samples.

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