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Review paper

Mugil cephalus as a Bioindicator of Coastal Ecosystem Health

Integrating Contaminant Bioaccumulation, Biomarkers, Multi-Stressor Toxicity, and Seafood Safety

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ABSTRACT

Mugil cephalus, commonly called the flathead grey mullet, lives in rivers, estuaries, lagoons, and coastal seas, and feeds on detritus and sediment-associated matter. These habits make it one of the most widely used sentinel fish species for coastal pollution monitoring. This review brings together recent literature, mainly from 2015 to 2025, on four connected topics: contaminant bioaccumulation, biological biomarkers, multi-stressor toxicity, and seafood safety in *M. cephalus*. Field and laboratory studies consistently show that metals such as lead, cadmium, chromium, copper, and zinc build up more in liver, kidney, and gill tissue than in muscle, while microplastics are commonly found in the gut and gills, and sometimes in liver and muscle as well. Biomarker studies show that pollution activates oxidative stress enzymes, damages genetic material, and causes visible injury in gill and liver tissue. Recent work also shows that fish size, season, and co-occurring stressors such as parasites and microplastics can change how strongly a fish responds to contamination. Several seafood-safety studies report that edible tissue of *M. cephalus* can exceed international safety limits for certain metals, and that the overall risk conclusion depends heavily on which risk index is applied. This review draws these findings into one framework and identifies major gaps in the current evidence, especially the shortage of combined-stressor studies and the limited understanding of microplastic–chemical interactions.

1. Introduction

Coastal and estuarine waters receive pollution from industry, agriculture, sewage, and shipping activity. These pollutants, including heavy metals, polycyclic aromatic hydrocarbons (PAHs), and microplastics, move from water into sediment and then into the tissues of fish and other organisms (3–5). Because fish sit high in the food web and are commonly eaten by humans, monitoring pollution in fish tissue links environmental health directly to public health.

Mugil cephalus, known as the flathead grey mullet, has become one of the most widely studied sentinel species for this purpose. It is euryhaline, meaning it can tolerate a wide range of salinity levels,

and it lives in rivers, estuaries, lagoons, and open coastal waters (1). It feeds mainly on detritus, algae, and bottom sediment, which brings it into close and repeated contact with sediment-bound contaminants (1,2). Because of its wide habitat range, its commercial importance, and its frequent presence in human diets, *M. cephalus* links environmental contamination with tissue-level biological effects and with human dietary exposure (6–8).

Earlier biomonitoring work with *M. cephalus* mostly measured metal residues in muscle or in the whole body (2). More recent studies, from about 2015 onward, have expanded this approach considerably. Researchers now combine tissue residue data with biochemical biomarkers, genetic damage markers, and tissue injury assessment, while also connecting these results to human seafood safety (9,10). This shift means that a single fish species can now provide evidence at several biological levels at once: chemical exposure, biological response, organ damage, and human health risk.

Despite this growth, published findings remain scattered across separate bodies of literature on metals, organic pollutants, and microplastics. Few papers attempt to connect these threads into a single picture, and even fewer examine how multiple stressors act together rather than alone. This review brings together recent evidence on *M. cephalus* as a coastal bioindicator, focusing on four connected areas: (i) bioaccumulation and tissue distribution of contaminants, (ii) biomarkers of exposure and biological injury, (iii) multi-stressor toxicity, and (iv) seafood safety and human health risk. The review also highlights where evidence remains thin, particularly regarding combined-stressor experiments and the interaction between microplastics and chemical pollutants.

2. *Mugil cephalus* as a Coastal Sentinel Species

M. cephalus is found worldwide in tropical and temperate coastal waters (1). It moves between fresh water, brackish water, and full seawater across its life, and adults often gather in large groups over sandy or muddy bottoms close to shore (1). This wide habitat use means the species is exposed to pollution sources from rivers, estuaries, lagoons, and open coastal waters, often within a single life cycle.

Its feeding habits add further value as a sentinel. *M. cephalus* is mainly a detritivore, meaning it feeds on dead organic matter, algae, and fine sediment particles, and it has a long gut suited to this diet (1,2). This feeding style brings it into direct contact with sediment-bound metals, organic pollutants, and settled microplastic particles (2,3). Because of this long gut, contaminant uptake in this species can be higher than in fish that feed mainly in open water (2).

Several field studies confirm that *M. cephalus* reliably reflects local pollution differences. In the Gulf of Annaba, Algeria, higher levels of metals in sediment were matched by higher levels of metals in fish muscle, and heavier metal contamination was linked to lower fish weight (5). In Lake Qaroun, Egypt, fish from more polluted zones near drain outlets had higher lead and cadmium levels and showed more tissue damage than fish from less polluted zones (4). In Libya, fish from a more polluted lake had higher lead and cadmium levels and poorer body condition than fish from a cleaner beach site (15). These site comparisons support the idea that *M. cephalus* responds in a measurable and fairly consistent way to local contamination levels, which is what makes it a dependable coastal sentinel.

Table 1 Summary of key field and laboratory studies on contaminant bioaccumulation and biomarker responses in *Mugil cephalus*

Study	Location	Tissue/Matrix	Contaminant	Key Finding
Ameur et al., 2015 (9)	Bizerte Lagoon, Tunisia	Gill	Persistent pollutants	Altered CAT/SOD, DNA damage, and gill lesions at the polluted site
Min et al., 2016 (10)	Laboratory, South Korea	Kidney, liver, gill, muscle	Hexavalent chromium (Cr6+)	Dose- and time-dependent accumulation in all tissues except muscle; gill as sensitive as liver
Ouali et al., 2018 (5)	Gulf of Annaba, Algeria	Water, sediment, muscle	Zn, Cu, Pb, Cd, Hg	Sediment metal rise increased muscle metal and reduced fish weight
Vasanthi et al., 2013 (11)	Ennore estuary, India	Gill, liver, muscle	Cu, Pb, Zn, Cd, Mn, Fe	Gill and liver held more metal than muscle; linked to histological injury
Rani, 2018 (16)	Kollidam estuary, India	Liver, gill, muscle	Multiple metals	Liver held more metal than gill or muscle for all metals tested
Guilhermino et al., 2021 (18)	Minho estuary, Portugal	GIT, gill, liver, muscle	Microplastics	Average 10 particles/fish; mostly fibres; found in muscle and liver too
Kılıç & Yücel, 2022 (19)	NE Mediterranean, Türkiye	GIT, gill	Microplastics	Highest GIT abundance among species; black fibres and polyethylene dominant
Atamanalp et al., 2022 (22)	East Anatolia, Türkiye	GIT, liver	Microplastics	High SOD/CAT activity linked with oxidative damage from MP exposure
Zhang et al., 2023 (3)	23 estuaries, South China	Surface water, whole fish	Microplastics	Fish particle shape/colour matched water column, supporting direct tracking
Tanhan et al., 2023 (13)	Pattani Bay, Thailand	Liver, muscle	Cd, Pb	Liver held more Cd/Pb/MDA than muscle; liver–muscle levels correlated

Indriyasari et al., 2023 (20)	East Java, Indonesia	Gill, stomach, intestine	Microplastics, plasticizers	Highest MP abundance in gills; plasticizer additives also detected
Alvariño et al., 2024 (6)	Callao, Peru	Muscle, liver	As, Cd, Pb, Cr, Se	Several elements exceeded international standards in both tissues
Hamad et al., 2024 (4)	Lake Qaroun, Egypt	Gill, liver, kidney, blood	Cu, Zn, Pb, Cd	Tissue-specific accumulation with histopathology and reduced blood parameters
Varea & Mani, 2024 (7)	Coastal Fiji	Edible tissue, bile	Metals, PAHs	Edible-tissue Cr exceeded WHO limit; higher genotoxicity at PAH-impacted site
El-Orfey et al., 2025 (15)	Benghazi Lake vs Qaminus Beach, Libya	Liver, gill, muscle	Pb, Cd	Higher metal burden and poorer condition factor at the polluted site
Salaah et al., 2025 (17)	Lake Manzala, Egypt	Muscle, gill, liver, kidney	Metals + parasite co-occurrence	Size-dependent accumulation; combined metal/parasite tissue pathology
Sasidharan et al., 2025 (14)	Kadinamkulam estuary, India	Water, sediment, liver, gill, muscle	Fe, Cr, Pb, Cu, Zn, Cd	Tissue order liver > gill > muscle; some metals exceeded USFDA limits
Meshram & Bhagat, 2025 (8)	Panvel Creek, India	Tissue (general)	Heavy metals	Elevated metal burden linked to habitat and feeding behaviour
Martins et al., 2025 (23)	Minho estuary, Portugal	Whole fish	Microplastics + season	Mullet most sensitive species; effects stronger in colder, low-food season

3. Bioaccumulation and Tissue Distribution of Contaminants

3.1 Heavy Metals

Across many field and laboratory studies, heavy metals do not spread evenly through the body of *M. cephalus*. Instead, metals build up more strongly in internal organs than in muscle. In a laboratory study using hexavalent chromium, accumulation increased with dose and exposure time in all tissues except muscle, with the kidney and liver holding the highest levels (10). In South Indian estuarine fish, metal levels followed the pattern liver > gill > muscle for iron, chromium, lead, copper, zinc, and cadmium (14). Older data from the Kollidam estuary reported a similar pattern, with the liver holding more metal than the gill or muscle for every metal tested (16). A similar tissue-order pattern has been reported from the Ennore estuary in India, where gill and liver metal levels exceeded muscle levels and were accompanied by tissue damage (11).

This organ-specific pattern makes biological sense. Gills are in constant contact with the surrounding water and often take up metals quickly, while the liver and kidney are the main organs responsible for breaking down and storing contaminants over a longer period (10,4,15). Because muscle usually holds the least metal, measuring muscle alone can underestimate how much contamination a fish has actually experienced, even though muscle remains the tissue most relevant to human diets (10,13,7).

Body size and local site conditions also shape how much metal builds up. In Lake Manzala, small fish had the highest iron and zinc levels in edible tissue, while larger fish built up more copper and cadmium (17). In Panvel Creek, *M. cephalus* showed higher metal levels than a comparison fish species, likely linked to its feeding behaviour near the sediment surface (8). These results show that a single snapshot of metal concentration can depend strongly on fish size, sampling site, and season, so comparisons between studies need to be made with care.

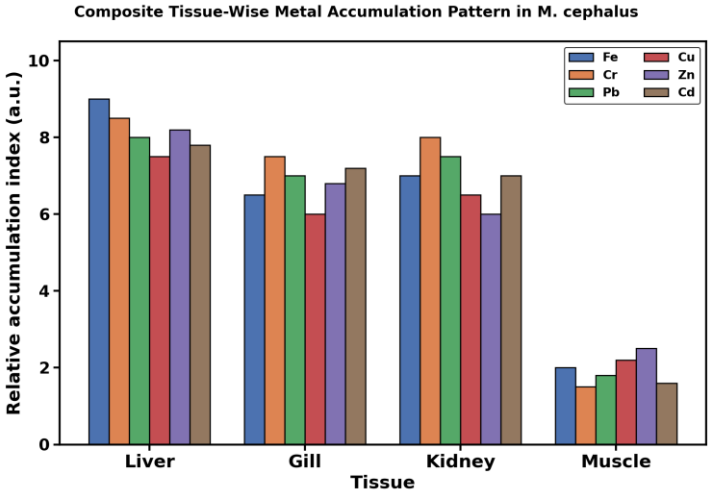


Fig. 1 Composite tissue-wise pattern of heavy metal accumulation reported across multiple field and laboratory studies of *Mugil cephalus*. Values are an illustrative relative index reflecting the consistently reported ranking liver ≈ kidney > gill > muscle, not measurements from a single dataset

3.2 Microplastics

Microplastic accumulation has become one of the fastest-growing areas of mullet research. In the Minho estuary in Portugal, *M. cephalus* carried an average of about ten microplastic particles per fish, mostly in the gut but with some particles also found in gills, liver, and muscle (18). Most particles were fibres. In the northeastern Mediterranean, mullet from the Asi River estuary had the highest gut microplastic levels among the species studied, with small black fibres and polyethylene the most common type (19).

Broader surveys support this pattern. Across 23 estuaries in South China, surface water was heavily polluted with microplastics, and fish carried an average of about seven particles each, with particle shape and colour closely matching what was found in the water (3). This close match between water and

fish particles supports the idea that mullet can be used to track microplastic pollution directly from the water column. In East Java, Indonesia, microplastics were most common in the gills, then the stomach, then the intestine, and chemical additives called plasticizers were also detected alongside the plastic particles (20). In Türkiye, nearly every fish examined contained microplastics, though the number of particles varied widely between individuals and did not depend on fish size, showing that local conditions matter more than fish body size (21).

Some recent work has moved from simply counting particles to measuring their biological effect. In East Anatolia, Türkiye, microplastic contamination was linked with signs of oxidative damage, and *M. cephalus* showed some of the highest antioxidant enzyme activity among the fish species studied (22). In the Minho estuary, fish with higher microplastic loads showed stronger overall stress signs, and mullet appeared more sensitive to this stress than carp or flounder, especially during colder, less productive seasons (23). This shows that the same microplastic burden can cause different biological effects depending on the surrounding environmental conditions.

4. Biomarkers of Exposure and Effect

Biomarkers are measurable biological changes that show a living organism has been exposed to, or affected by, environmental contaminants (12). They range from simple biochemical changes to visible tissue damage, and using several biomarkers together gives a more complete picture of pollution stress than chemical residue data alone (12).

4.1 Oxidative Stress Biomarkers

Many pollutants cause the overproduction of reactive molecules inside cells, leading to oxidative stress. Fish respond to this by activating antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione-S-transferase (GST) (12). In Bizerte Lagoon, Tunisia, mullet from a polluted site showed altered CAT and SOD activity along with impaired DNA and visible gill damage, showing that biochemical and structural responses can appear together (9). A laboratory study using hexavalent chromium found that GST and SOD activity changed in liver and gill, while liver glutathione and metallothionein, a metal-binding protein, appeared to support detoxification (10). Importantly, this same study found that gill tissue was about as sensitive to chromium as liver tissue, which supports using gill tissue, and not only muscle, for early pollution warning (10).

In Pattani Bay, Thailand, cadmium, lead, and a marker of lipid damage called malondialdehyde were all higher in liver than in muscle across several coastal fish species, including *M. cephalus*, while antioxidant enzyme levels varied between species and tissues (13). In Lake Qaroun, tissue injury in gill, liver, and kidney was linked with lower red blood cell counts, haemoglobin, and haematocrit in fish from more polluted areas, showing that oxidative and blood-related changes can occur together under long-term pollution exposure (4).

4.2 Genotoxicity Biomarkers

Genotoxicity biomarkers detect damage to genetic material. One common method looks for micronuclei, small extra bodies that form in blood cells when chromosomes are damaged. In Fiji, mullet from the more polluted Ba River Delta had higher levels of biliary PAHs, higher GST activity, higher lipid peroxidation, and more micronuclei and other abnormal blood-cell nuclei compared with fish from a less polluted bay (7). This study is valuable because it links a class of organic pollutants, PAHs, directly with genetic damage in a wild, commercially caught fish population (7).

4.3 Histopathological Biomarkers

Histopathology, the microscopic study of tissue damage, gives direct visual evidence of biological injury. In Bizerte Lagoon, polluted-site fish showed gill lesions including thickening, abnormal cell growth, shortening, and fusion of the thin gill folds used for breathing (9). In Ennore estuary, India, mullet from a polluted site showed liver changes such as fat droplet build-up and gill changes such as more mucus-producing cells, both linked to metal exposure (11). In Lake Manzala, fish size influenced not only metal levels but also the pattern of tissue damage together with infection by a parasite called Myxobolus, showing that pathology can result from more than one stressor acting together (17).

5. Multi-Stressor Toxicity

Most published studies on *M. cephalus* still test one contaminant at a time. However, real coastal environments expose fish to several stressors together, including metals, organic pollutants, microplastics, parasites, and seasonal changes in temperature and food availability. A small but growing number of studies show that these combined stressors can act in ways that are stronger, weaker, or different from what a single stressor would cause alone (23,17,7).

In the Minho estuary, fish carrying higher microplastic loads had 1.2 to 1.8 times higher overall stress scores, and mullet were more affected than carp or flounder (23). Importantly, the effect of microplastics was stronger during colder months with lower food availability, showing that season and

nutrition status can change how strongly a fish reacts to the same pollutant load (23). In Lake Manzala, fish size affected not only how much metal built up but also how severe the combined tissue damage from metals and parasite infection became, and the authors described these effects as acting together rather than separately (17). In Fiji, the combination of metal and PAH exposure produced stronger biomarker responses at the more heavily exposed site than would be expected from either pollutant class alone (7).

Beyond *M. cephalus* specifically, the wider fish toxicology literature also supports the idea that combined stressors often behave differently from single stressors. A recent meta-analysis of microplastics combined with other emerging pollutants in fish found that combined exposure often increased oxidative stress and other harmful effects compared with either stressor alone, although the length of exposure did not always predict how strong the effect would be (25). Microplastics can also act as carriers for other pollutants, since chemicals can stick to plastic particles and then be released once inside the fish gut, adding another route by which combined exposure can occur (26).

This evidence suggests that single-contaminant studies, while useful, may not fully describe the risk that coastal fish actually face. Studies that test two or more stressors together, especially metals with microplastics, or pollution together with seasonal temperature change, remain uncommon for *M. cephalus* and represent an important gap in the current evidence base.

6. Seafood Safety and Human Health Risk

Because *M. cephalus* is widely eaten, contaminant levels in its edible tissue directly matter for human health. Several recent studies report contaminant levels exceeding international food-safety limits at least at some sites. In Algeria, muscle levels of lead, zinc, and cadmium exceeded safety standards at several sites, and the authors flagged fish from these areas as potentially unsafe for regular consumption (5). In Peru, arsenic, cadmium, lead, chromium, and selenium all exceeded international standards in both muscle and liver tissue (6). In Fiji, chromium in edible tissue exceeded World Health Organization limits at both sampling sites, even though mercury and cadmium levels stayed low (7).

Human health risk from seafood is often measured using a small set of standard indices. The target hazard quotient (THQ) estimates non-carcinogenic risk from a single contaminant, while the hazard index (HI) adds up risk across several contaminants eaten together. Values above 1 generally indicate a possible health concern. In Lake Manzala, single-contaminant THQ values stayed below 1, yet regular consumers, especially those eating smaller fish, faced a combined HI above 1, showing that cumulative exposure across several metals can create risk even when no single metal looks dangerous on its own (17). By contrast, in the Kadinamkulam estuary in South India, zinc, cadmium, and lead exceeded USFDA limits, but the overall human-health index still placed the fish in a non-carcinogenic category (14). This contrast is important: it shows that the conclusion of a seafood-safety study can depend heavily on which specific index and calculation method the researchers use, not only on the raw contaminant levels measured.

Microplastic-related seafood-safety data are less developed than metal-related data. Studies from the Bay of Bengal and elsewhere have detected substantial microplastic loads in commercially important marine fish, including in gill and gut tissue, and have started applying pollution-load indices to describe ecological risk, but very few studies yet convert microplastic counts into a defined human-health risk value for a species that people frequently eat (24). This is an important gap, since microplastics are increasingly found in edible tissue and not only in the gut, which mullet studies have already shown is possible (18).

Taken together, the seafood-safety literature shows that *M. cephalus* can carry contaminant levels above accepted safety limits in specific polluted locations, but overall risk classification depends strongly on which metals are measured, which tissue is tested, and which risk index is applied. This variability means that a general statement such as "mullet is safe" or "mullet is unsafe" cannot be made without specifying the exact location, season, and contaminant panel involved.

Table 2 Seafood safety findings and human health risk outcomes for *Mugil cephalus* across selected studies

Study	Location	Risk Index Used	Outcome
Ouali et al., 2018 (5)	Gulf of Annaba, Algeria	Standard comparison	Pb, Zn, Cd exceeded international standards in muscle at some sites
Alvariño et al., 2024 (6)	Callao, Peru	Standard comparison	As, Cd, Pb, Cr, Se exceeded standards in muscle and liver
Varea & Mani, 2024 (7)	Coastal Fiji	WHO permissible limit	Edible-tissue Cr exceeded WHO limit at both sampling sites
Sasidharan et al., 2025 (14)	Kadinamkulam estuary, India	USFDA limit; health-risk indices	Zn, Cd, Pb exceeded USFDA limits; overall classed non-carcinogenic
Salaah et al., 2025 (17)	Lake Manzala, Egypt	THQ, HI	Individual THQ < 1, but cumulative HI > 1 for habitual consumers of small fish

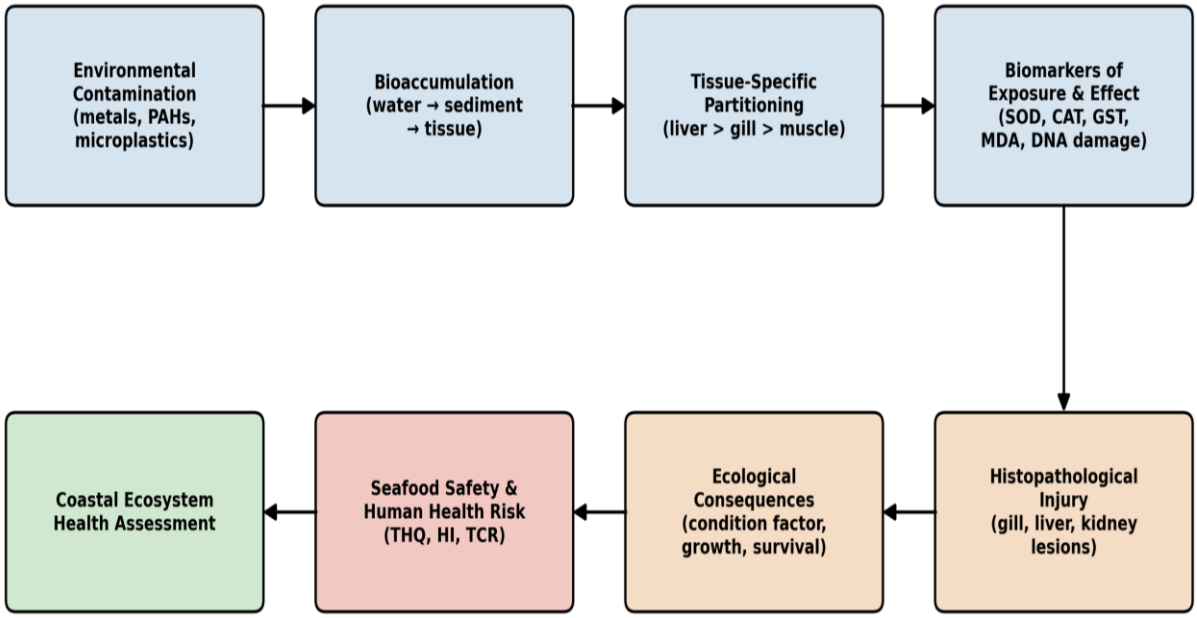


Fig. 2 Integrative framework linking coastal contamination, tissue-specific bioaccumulation, biomarker responses, pathology, ecological consequences, and seafood safety in *Mugil cephalus*

7. Research Gaps and Future Directions

Based on the reviewed literature, several gaps stand out.

First, most studies still measure a single stressor at a time. Real coastal pollution rarely occurs this way, so more studies that test combined stressors, such as metals with microplastics or pollution together with seasonal warming, are needed to understand real-world risk (23,17,25).

Second, microplastic research on *M. cephalus* mostly counts particles and identifies polymer type, but rarely links these numbers to a measurable biological effect or a formal human-health risk value (18,19,20,21). Bringing microplastic studies up to the same level of detail as metal studies, including standard risk indices, would make comparisons across pollutant types possible.

Third, biomarker studies and seafood-safety studies are often published separately, even when they use fish from the same site. Bringing these two types of data together within a single study design would allow researchers to connect biological injury directly with dietary risk to people (9,17).

Fourth, most current evidence comes from relatively short-term or single-season sampling. Long-term monitoring across multiple years and seasons would help separate real pollution trends from natural short-term variation caused by breeding cycles, temperature, or rainfall (17,23).

Finally, standardising how future studies report sample size, tissue choice, exposure time, and risk-index calculation would make it far easier to compare results across countries and build a global picture of coastal pollution using this single, widely available sentinel species (2).

8. Conclusion

Mugil cephalus is more than a convenient fish to sample. Its wide habitat range, its detritus-feeding behaviour, and its place in human diets make it a strong, biologically meaningful sentinel for coastal ecosystem health. Recent literature confirms that this species reliably reflects local pollution differences, shows measurable tissue-specific contaminant build-up, produces clear biochemical and structural biomarker responses, and can carry seafood-safety risks that matter to regular consumers. At the same time, the evidence remains uneven: single-stressor studies far outnumber combined-stressor studies, microplastic research remains largely descriptive, and biomarker and human-health data are rarely combined in one study. Addressing these gaps would allow *M. cephalus* to fulfil its full potential as an integrated bioindicator, connecting environmental contamination, biological injury, and human seafood safety within one coherent evidence framework.

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