

Ocean predators as indicators of nano- and microplastic prevalence in pelagic food webs

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Abstract

Quantifying nano- and microplastics (NMPs) in ocean predators is fundamental to understanding the prevalence of these contaminants and potential impacts on ecosystem health. Pyrolysis gas chromatography tandem mass spectrometry with lipid correction was used to determine NMP concentrations and polymer composition in the muscle tissue of two pelagic predators (dolphinfish [*Coryphaena hippurus*], yellowfin tuna [*Thunnus albacares*]) across the Atlantic, Pacific, and Indian Oceans. Five polymers (polycarbonate, polyethylene, polypropylene, polyvinyl chloride, nylon-66) accounted for ~99% of the total NMP concentration detected in both species. Differences in NMP concentrations were observed between the two species, with body burdens often markedly lower in yellowfin tuna relative to dolphinfish within the same region or ocean basin. Polyethylene was the dominant polymer present in the muscle tissue of both species followed by nylon-66, polypropylene, and polyvinyl chloride. Spatial variation in polymer composition and NMP concentrations was observed, indicating that NMP signatures may serve as markers of an individual's recent or integrated exposure history. No relationship between NMP body burden and trophic position was observed for either species, with trophic position of yellowfin tuna consistently higher than dolphinfish in nearly all regions examined despite displaying lower NMP concentrations. Our findings establish that NMPs are pervasive in the muscle tissue of higher-order predators in pelagic ecosystems across all three ocean basins.

Keywords Microplastics · Pelagic ecosystem · Tuna · Dolphinfish · Migratory species · Biomagnification

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Introduction

The production of synthetic plastics contributes significantly to environmental pollution in marine ecosystems^{1,2}. Pathways of plastics entering oceans are varied and originate from both terrestrial and marine sources including river runoff, atmospheric transport, shipping, fishing activities, and illegal dumping^{3–6}. Degradation and fragmentation of many larger (macro-) plastics by photolysis (sunlight/UV radiation), biodegradation (microorganisms), and mechanical processes⁷ lead to the formation of nano- (< 1 µm) and microplastics (1 µm to 5 mm) (hereafter NMPs), which are increasingly implicated as contaminants of emerging concern (CECs)^{8,9}. A wide variety of NMP polymers are common in marine environments throughout major ocean basins¹⁰, and these synthetic compounds represent significant threats to marine ecosystems, often altering processes at the base of the food web. These ecological alterations include reductions in phytoplankton production and shift in community structure of autotrophs^{11,12} as well as decreases in grazing rates by secondary consumers (i.e., zooplankton)¹³. NMPs contain numerous chemical compounds that adds to their intrinsic toxicity¹⁴, while also having the capacity to adsorb and concentrate other environmental contaminants (e.g., per- and polyfluoroalkyl substances, PFAS), releasing them into the tissues of consumers, which can result in negative additive or synergistic effects on predators and associated fauna¹⁵.

All trophic levels of marine food webs, ranging from autotrophs to apex predators, are exposed to varying levels of contaminants, including NMPs¹⁶. These contaminants regularly enter food webs via primary consumers (i.e., herbivores) such as zooplankton or through small planktivorous fishes¹⁷. Bioaccumulation and biomagnification of several classes of contaminants have been linked to both predator size/age and their trophic position with larger, older, and higher trophic-level consumers often displaying elevated contaminant body burdens^{18,19}. As a result, higher order consumers may be at an elevated risk of metabolic and neurodevelopmental disorders, depleted energy stores, reduced fertility, and lower growth rates^{10,20}. All of which can compromise the health and survival of pelagic predators, potentially causing cascading effects through food webs that may alter the function and resiliency of marine ecosystems²¹. Apart from potential ecological consequences, many top predators found in open ocean ecosystems are large pelagic fishes that are important components of regional fisheries and readily consumed by humans²², possibly resulting in adverse effects on human health^{23–25}.

A significant fraction of higher-order, pelagic predators found in tropical and temperate oceans are highly migratory, and thus these taxa may serve as conduits for the wider dispersal of NMPs across ecosystems and ocean basins. Here, we characterize ocean-scale variability in NMP concentration and polymer composition of circumglobal pelagic fishes from multiple regions in the Atlantic, Pacific, and Indian Oceans. Two species with cosmopolitan distributions and common constituents of pelagic food webs were selected for this investigation: dolphinfish (*Coryphaena hippurus*) and yellowfin tuna (*Thunnus albacares*). The central aim of this investigation was to characterize inter- and intra-ocean basin trends in NMP concentrations in the muscle tissue of these predators using a novel analytical approach that applies pyrolysis gas chromatography coupled with triple quadrupole mass spectrometry (Py-GC-qQq-MS) to quantify NMP concentrations and polymer types in muscle tissue²⁶. The Py-GC-qQq-MS approach is a significant advancement over traditional microscopic and spectroscopic assessments since it provides an integrated measure of NMPs in biological tissue (muscle) rather than a snapshot from particle counts of NMPs present in the digestive tract of these predators. In addition to characterizing species- and region-specific trends in NMP concentration and polymer composition, we investigated the relationship between NMP body burden and trophic position of these predators by using compound-specific stable isotope analysis of amino acids (CSIA-AA) in $\delta^{15}\text{N}$ ($\delta^{15}\text{N}_{\text{AA}}$). The inclusion of both large pelagic species with varied life history and foraging traits across major ocean basins will help elucidate the pervasiveness of NMPs in open ocean food webs.

Materials and methods

Sample collections

Dolphinfish and yellowfin tuna were collected from five regions in both the Atlantic Ocean and Pacific Ocean, and a single region in the Indian Ocean. All muscle tissue was procured from port sampling harvested (dead) fish. Samples were collected from 2021 to 2024 by recreational, artisanal, and commercial anglers from the 11 regions. In the Atlantic Ocean, regions included the Northwest Atlantic Ocean, Equatorial Atlantic Ocean, Caribbean Sea, and two marginal seas (Gulf of Mexico and Mediterranean Sea) (Table 1). Five regions were also sampled in the Pacific Ocean: Northwest Pacific Ocean, Northcentral Pacific Ocean, Northeast Pacific Ocean, Equatorial Pacific Ocean, and South Pacific Ocean. One region was sampled in the Southwest Indian Ocean. Regional samples were typically comprised of individuals from multiple sampling location, and larger specimens (adults) were targeted to minimize the influence of size on NMP concentrations for each species (Table 1). It is important to acknowledge that both species are migratory and have the capacity to cross into new regions; however, the broad geographic separation of regional sampling areas in this study reduced the possibility of this affecting spatial comparisons. Apart from yellowfin tuna being absent from one region (Mediterranean Sea), sample sizes per region (6 per species) were equal for all 11 regions (total: dolphinfish $n=66$; yellowfin tuna $n=60$). Muscle tissue was typically sampled from the anterior dorsal area of each specimen and kept on ice and stored at $-20\text{ }^{\circ}\text{C}$ until samples were freeze-dried. To reduce risk of contamination, 1–2 mm of all sides of the muscle tissue sample were removed with a stainless-steel scalpel before material was extracted for digestion. The scalpel was cleaned with GC grade methanol between samples. Digestion occurred in furnaced glass tubes covered with lab grade foil.

Nano/microplastic (NMP) quantification

An accelerated solvent extraction (ASE) system (Dionex ASE 350) was used to determine total lipid content in freeze-dried muscle tissue. An extraction filter (Dionex, Thermo Fisher Scientific) was placed at the bottom of a clean stainless-steel ASE extraction cell (34 ml) and ground muscle tissue ($\sim 25\text{ mg}$) was added to the cell with

Table 1 Species- and region-specific variation in mean $\sum$ NMP concentrations ($\mu\text{g g}^{-1}$ DW) in the muscle tissue of dolphinfish and yellowfin tuna. $\sum$ NMP concentrations were based on the sum of the five primary polymers detected (PC, PE, PP, PVC, N66) for each individual and average by species for each region. Primary sampling location within each region also denoted. Standard deviation (1 SD) around means also shown.

Ocean/Region	Primary sampling area	Dolphinfish				Yellowfin Tuna			
		N	Mean FL (cm)	$\sum$ NMP ($\mu\text{g g}^{-1}$ DW)	1 SD	N	Mean FL (cm)	$\sum$ NMP ($\mu\text{g g}^{-1}$ DW)	1 SD
Atlantic Ocean									
Northwest	South Atlantic Bight	6	109	14,362	9,461	6	104	7,845	3,852
Gulf of Mexico	Northern Gulf of Mexico	6	117	6,277	2,048	6	125	2,346	3,111
Mediterranean	Balearic, Tyrrhenian, Aegean Seas	6	61	15,087	7,794				
Northcentral	Caribbean Sea	6	86	16,026	10,522	6	98	5,013	2,120
Equatorial	Brazil	6	122	15,910	5,865	6	122	3,261	3,258
All Atlantic		30		13,532		24		4,616	
Pacific Ocean									
Northwest	Taiwan	6	93	18,842	9,887	6	134	1,785	1,476
Northcentral	Hawaiian Islands	6	102	6,272	2,516	6	117	917	519
Northeast	California/Mexico	6	91	9,932	2,879	6	NA	12,241	11,801
Equatorial	Panama	6	95	6,966	2,343	6	116	7,087	5,427
Southwest	E. Australia	6	122	8,357	2,638	6	138	2,767	2,318
All Pacific		30		10,074		30		4,959	
Indian Ocean									
Southwest	Reunion Island	6	104	6,390	1,525	6	117	8,274	11,620

sand used to fill the void space. Next, a mixture of dichloromethane and hexane (1:1) at 100 °C and 1500 psi was used for the extraction. For each muscle tissue sample, extraction involved a 5-min preheating phase, 5-min heating phase, two 20-min static periods with 40% rinse, followed by a 5-min purge. Recovered solvent extracts were collected in amber glass vials and allowed to evaporate to dryness under a fume hood. Before and after weights of glass vials were used to calculate tissue lipid content (% of dry weight, Table S1).

Freeze-dried muscle tissue for all individuals was digested using porcine pancreatic enzyme (Pez) combined with tris hydrochloride solution (Tris)²⁶. The combined Pez/Tris solution served to dissolve the muscle tissue matrix, releasing NMPs for quantification. Digested samples were then subjected to vacuum filtration through a combusted glass fiber filter (25 mm, 0.7 µm), which was rinsed with milli-Q water and dried for approximately 24 h at 38 °C. Dried filters were cut with a brass cork borer to remove unused filter area. The remaining filters were folded and placed in pyrolysis stainless steel cups pretreated with the internal standard poly(4-fluorostyrene) (PFS) and topped with 5 mg of CaCO₃ and quartz wool in preparation of pyrolysis gas chromatography. NMPs were quantified using a Frontier Auto-Shot AS-2020E sampler and EGA/PY 3030D multi-shot pyrolyzer coupled with an Agilent 8890 gas chromatograph and Agilent 7010B triple quadrupole mass spectrometer (Py-GC-qQq-MS). Pyrolyzates were chromatically separated on an ultra-alloy capillary column before being introduced to the MS detector (Table S2). Injector split ratio, split flow, temperature, and purge flow followed the previously established protocol²⁵.

The MS detector was regularly autotuned using Agilent ChemStation software (V. 10) and quantification of NMP polymers was based on dynamic multiple reaction monitoring (dMRM) using characteristic product ions. Calibration standards were a homogenous mixture of Frontier plastic polymers (Frontier Labs, Lot # 21101501) and inert CaCO₃ and quartz wool fillers, which were used to improve combustion efficiency and reduce char build-up. The Py-GC-qQq-MS approach was used to quantify 11 commonly quantified polymers in the muscle tissue of the two pelagic fishes: acrylonitrile butadiene styrene (ABS), nylon-66 (N66), nylon-6 (PA), polycarbonate (PC), polyethylene (PE), polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), polypropylene (PP), polystyrene (PS), polyurethane (PUR), and polyvinyl chloride (PVC).

Accurate identification of NMPs relied on detailed quality assurance and quality control protocols. Pez/Tris batch solutions were filtered with combusted (450 °C) glass fiber filters (GFF, 0.7 µm) before use to remove plastic contamination²⁶. Each analytical batch included ≥ 2 procedural blanks containing the filtered Pez/Tris solution, GFF filter, internal standard, CaCO₃, and quartz wool were used for the batch tissue samples. Mean procedural blank amounts ranged from 4 to 31 µg for individual plastics and were subtracted from results. Limits of detection (LOD; signal-noise-ratio of 3) ranged from 1 to 126 ng and limits of quantification (LOQ, signal-noise-ratio of 10) across plastics (Table S2)²⁶. Calibration curves ranging from 0.2 to 260 µg were fitted with a quadratic regression to achieve correlation coefficients (R^2) > 0.999 (Table S3).

Lipid interference in NMP quantification with Py-GC-qQq-MS can occur^{27,28} and, as a result, NMP concentrations were corrected by applying a mathematical lipid correction method based on total lipid content (Table S4)²⁶. After correction, method accuracy established with co-spiked NMP standards ranged from 94 to 111% for N66, PE, PP, and PVC (N66 $95 \pm 17\%$, PE $111 \pm 11\%$, PP $102 \pm 5\%$, PVC $94 \pm 7\%$), indicating applied lipid corrections were appropriate.

Trophic position

Compound-specific stable isotope analysis of amino acids (CSIA-AA) in $\delta^{15}\text{N}$ ($\delta^{15}\text{N}_{\text{AA}}$) was used to estimate trophic position of each fish in relation to NMP concentration in their muscle tissue. CSIA-AA of $\delta^{15}\text{N}_{\text{AA}}$ was quantified using a Thermo Trace GC 1310 gas chromatograph coupled to a Thermo Scientific Delta V Advantage isotope ratio mass spectrometer via a GC IsoLink II combustion interface (GC-C-IRMS; Thermo Fisher Scientific, Waltham, MA) at the University of California Davis Stable Isotope Facility (UCD-SIF). Nitrogen isotope ratios of amino acids were reported using delta notation (Eq. 1), where R_{Sample} represents the ratio of the heavy to

light nitrogen isotope in the sample and R_{Standard} represents the ratio of the heavy to light nitrogen isotope in the standard for each amino acid quantified.

$$\delta^{15}\text{N}_{\text{AA}} (\text{‰}) = ([R_{\text{Sample}}/R_{\text{Standard}}] - 1) \times 1000 \quad (1)$$

Delta values were reported relative to internal standards: norleucine and amino acid reference mixtures developed by UCD-SIF. The mean standard deviation for reference materials was 0.66‰.

Trophic position was estimated using $\delta^{15}\text{N}_{\text{AA}}$ weighted means of select source (glycine, lysine, phenylalanine) and trophic (alanine, glutamic acid, leucine) amino acids²⁹. We utilized the CSIA-AA trophic position method previously described³⁰, which applied updated trophic discrimination factor and reduced variation in trophic position estimates by including multiple source and trophic amino acids. Trophic position was estimated using Eq. 2, where λ represents the trophic level of primary producers, β represents the isotopic difference between $\delta^{15}\text{N}_{\text{Trophic}}$ and $\delta^{15}\text{N}_{\text{Source}}$ in primary producers, and Δ represents the difference in enrichment factors between $\delta^{15}\text{N}_{\text{Trophic}}$ and $\delta^{15}\text{N}_{\text{Source}}$ with each trophic level. λ , β , and Δ were set to 1, 3.6, and 5.7, respectively and based on³⁰.

$$\text{Trophic Position} = \lambda + (\delta^{15}\text{N}_{\text{Trophic}} - \delta^{15}\text{N}_{\text{Source}} - \beta) / \Delta \quad (2)$$

Data analysis

Analysis of variance (ANOVA) was used to test for regional differences in NMP concentrations of selected species, with reported ΣNMP representing the summed concentration ($\mu\text{g g}^{-1}$ dry weight [DW]) of the five primary NMP polymers quantified for each individual fish. Significant findings were further evaluated using Tukey HSD to determine factor levels (i.e., regions) that were significantly different from one another. Since samples were purposely restricted to adults within a limited size range for each species, variation in fish size was limited and no adjustment was performed for size differences among regions. Pearson's correlation coefficients were also calculated based on concentrations of the five primary polymers found in the muscle tissue of dolphinfish and yellowfin tuna to determine relationships between NMP polymers. Canonical discriminant analysis (CDA) was used to display multivariate NMP means in a reduced space with CDA biplot vectors included to show the influence of specific polymers on ocean-basin association. Quadratic discriminant function analysis (QDFA) was then used to determine the classification accuracy of individuals to their respective ocean basin using their NMP signature and based on cross validation (jack-knifed) approach. QDFA was applied to NMP data since it does not require the homogeneity of covariance matrices assumption among regions, and it is relatively robust to moderate deviations from normality. The relationship between ΣNMP and CSIA-AA based trophic position was evaluated for each species separately using standard least squares regression analysis with significance defined slopes significantly different from zero. Only individual fish with paired values of ΣNMP and CSIA-AA based trophic position were used to develop species-specific relationships, which reduced the sample size of dolphinfish ($n=28$) included for this specific analysis. For all statistical testing α was set at 0.05.

Results

Eleven NMPs were identified in the tissue of pelagic fishes using Py-GC-qQq-MS, with five polymers, polycarbonate (PC), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), nylon-66 (N66), accounting for over 99% of the total NMP concentration detected across all regions and between species (Table 1). Moreover, PC, PE, PP, PVC, and N-66 were commonly present in the muscle tissue of both species (>50% frequency of occurrence), with PE and N66 detected in 89.8% and 98.4% of the individual fish assayed, respectively (Table S1). Concentrations of the remaining six NMP polymers were often negligible, and frequency of occurrence was relatively low and highly variable across regions and species: acrylonitrile butadiene styrene (ABS; not detected),

nylon-6 (PA; 13.3%), polyethylene terephthalate (PET; 12.5%), polymethyl methacrylate (PMMA; 14.1%), polystyrene (PS; 35.2%), and polyurethane (PUR; 0.0%) (Table S1). Given that PC, PE, PP, PVC, N-66 were consistently detected in both species and comprised the bulk of NMP concentration, characterization and analysis of species- and region-specific variation in NMP body burdens focused on these five polymers.

Significant regional variation in $\sum$ NMP concentration ($\mu\text{g g}^{-1}$ DW) based on the five polymers (PC, PE, PP, PVC, N66) was detected for dolphinfish across the 11 areas sampled (ANOVA, $F_{10,55} = 3.528$, $p < 0.01$, Table 1). Muscle tissue $\sum$ NMP concentrations of dolphinfish also varied among regions (i.e., intra-ocean) within one of the ocean basins investigated. In the Atlantic Ocean, $\sum$ NMP concentrations of dolphinfish were not significantly different among the five regions sampled (ANOVA, $F_{4,25} = 1.693$, $p > 0.05$). The lowest $\sum$ NMP body burdens were observed for dolphinfish from the Gulf of Mexico (mean ± 1 SD, $6,227 \pm 2,048 \mu\text{g g}^{-1}$ DW), while individuals assessed from the four other regions in the Atlantic Ocean (Northwest Atlantic, Equatorial Atlantic, Caribbean Sea, Mediterranean Sea) displayed levels often twofold higher than the Gulf of Mexico (ca. 14,000 and 16,000 $\mu\text{g g}^{-1}$ DW); nevertheless, pairwise comparisons indicated body burdens in these regions were statistically similar to the Gulf of Mexico (Tukey HSD, $p > 0.05$). Intra-ocean variation was also detected within regions sampled in the Pacific Ocean (ANOVA, $F_{4,25} = 6.246$, $p < 0.01$). Muscle tissue $\sum$ NMP concentrations of dolphinfish from the Northcentral and Equatorial Pacific regions ($6,272 \pm 2,516$ and $6,996 \pm 2,343 \mu\text{g g}^{-1}$ DW, respectively) were lower than the three other regions sampled in this ocean basin. The highest $\sum$ NMP concentrations occurred for dolphinfish sampled in the Northwest Pacific region, and levels in this region ($18,842 \pm 9,887 \mu\text{g g}^{-1}$ DW) were significantly higher than all four other regions sampled in the Pacific Ocean (Tukey HSD, $p < 0.05$ for all paired comparison). $\sum$ NMP concentrations for the one region sampled in the Southwest Indian Ocean ($6,390 \pm 1,525 \mu\text{g g}^{-1}$ DW) was comparable to the lowest body burdens observed in both the Atlantic and Pacific Oceans.

Distinct regional differences in muscle tissue $\sum$ NMP concentrations of yellowfin tuna were also present for individuals across the 10 regions sampled (ANOVA, $F_{9,50} = 2.375$, $p < 0.05$, Table 1), and regional trends were generally consistent with spatial patterns observed for dolphinfish. Significant differences in $\sum$ NMP concentrations of yellowfin tuna were present at the intra-ocean scale in the Atlantic Ocean (ANOVA, $F_{4,23} = 3.187$, $p < 0.05$), with the lowest and highest $\sum$ NMP body burdens observed for individuals sampled in the Gulf of Mexico ($2,343 \pm 3,111 \mu\text{g g}^{-1}$ DW) and Northwest Atlantic ($7,845 \pm 3,852 \mu\text{g g}^{-1}$ DW). A significant pairwise difference in $\sum$ NMP body burden was only detected for these two regions in the Atlantic Ocean (Tukey HSD, $p < 0.05$). Similarly, significant region-specific differences in $\sum$ NMP concentrations of yellowfin tuna were observed across the five regions sampled in the Pacific Ocean (ANOVA, $F_{4,24} = 3.609$, $p < 0.05$). Yellowfin tuna from the Northcentral Pacific ($917 \pm 519 \mu\text{g g}^{-1}$ DW) displayed the lowest $\sum$ NMP body burden relative to all other regions assessed in the Pacific Ocean. Yellowfin tuna from the Northeast Pacific region displayed the highest and most variable $\sum$ NMP mean concentration ($12,241 \pm 11,801 \mu\text{g g}^{-1}$ DW), and elevated $\sum$ NMP concentrations in this region were significantly different from the two regions with the lowest levels: Northcentral and Northwest Pacific ($1,785 \pm 1,476 \mu\text{g g}^{-1}$ DW) (Tukey HSD, $p < 0.05$). In the Indian Ocean, yellowfin tuna from the one region sampled had higher $\sum$ NMP body burdens ($8,274 \pm 11,620 \mu\text{g g}^{-1}$ DW) than mean values observed for both the Atlantic and Pacific Oceans (Table 1).

Regional variation in percent composition of the five primary NMP polymers (PC, PE, PP, PVC, N-66) highlighted the dominance of PE and N66 in the body burdens of both species. For dolphinfish, PE was the dominant polymer detected, accounting for the largest fraction of the mean NMP concentration (pooled regions) in the Atlantic (65%), Pacific (60%), and Indian (43%) Oceans (Fig. 1). N66 was the second most abundant polymer in the muscle tissue of dolphinfish from the Atlantic (16%) and Pacific (21%) Oceans, ranging from 15% in the Northwest Atlantic to 35% in the Northcentral Pacific. N66 accounted for the highest fraction of NMP polymers for dolphinfish in the Indian Ocean (45%), with percent composition of this polymer similar to PE. For yellowfin tuna, PE again accounted for the largest fraction of quantified polymers in the Atlantic (44%), Indian (61%), and Pacific (53%) Oceans; however, PE contribution to overall polymer composition was more variable among regions sampled in both the Atlantic and Pacific Oceans. Overall mean percent composition of N66 in yellowfin tuna was relatively consistent among the three oceans (range: 30 to 32%), but variable among the regions

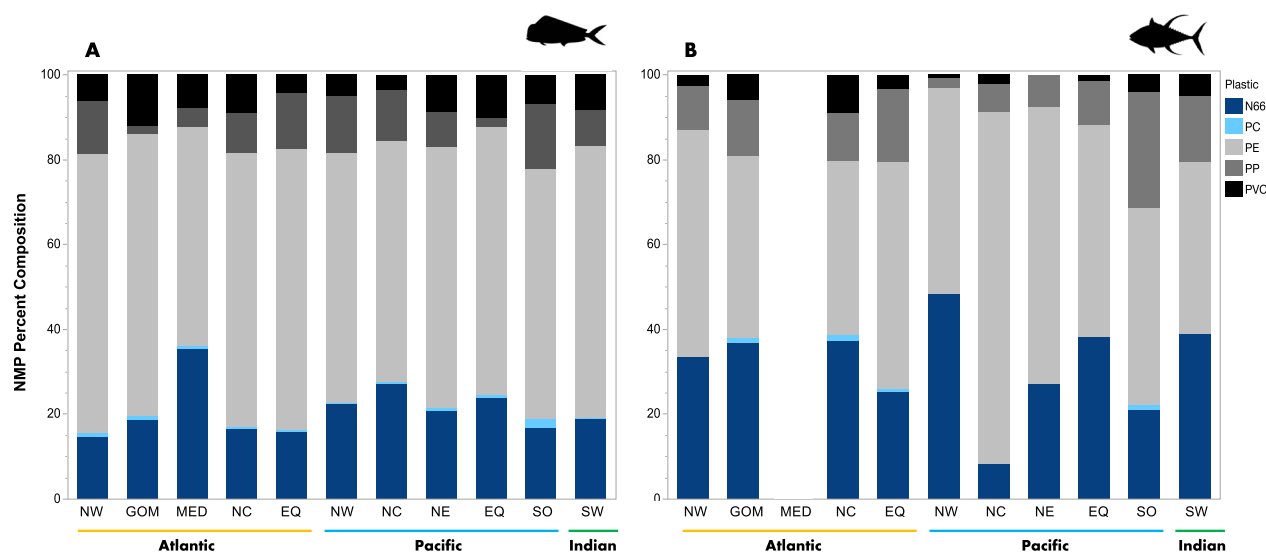


Fig. 1 Percent composition of the five primary NMP polymers (PC, PE, PP, PVC, N66) quantified in the muscle tissue of dolphinfish (**A**) and yellowfin tuna (**B**) for all regions sampled from the Atlantic, Pacific, and Indian Oceans. Composition based on all individuals collected within each region. Region codes: Atlantic (NW=Northwest, GOM=Gulf of Mexico, MED=Mediterranean Sea, NC=Northcentral, EQ=Equatorial); Pacific (NW=Northwest, NC=Northcentral, NE=Northeast, EQ=Equatorial, SO=Southwest); Indian (SW=Southwest).

sampled within the Atlantic and Pacific Oceans; lowest and highest contributions of this polymer were observed for individuals from the Northcentral Pacific (8%) and Northwest Pacific (50%), respectively. For both dolphinfish and yellowfin tuna, percent composition of PP and PVC was minor to modest, with PP typically accounting for a larger percentage of the NMP body burden than PVC. PC was consistently present in the muscle tissue of both species but at low concentrations and often only accounted for 1–2% of total NMP body burden.

Relationships among the five primary NMP polymers in the muscle tissue of both dolphinfish and yellowfin tuna was investigated, and significant correlations between polymer types were observed (Pearson's $p < 0.05$; Fig. 2). For dolphinfish, paired comparisons between NMP polymers resulted in several significant correlations and all were positive. The strength of associations between NMP polymers was highest between PE and PP (0.79), with moderate correlations present for PE – PVC, N66 – PE, N66 – PP (0.4–0.6). PVC was significantly correlated with three of four polymers, albeit the strength of the relationships was less than 0.4 for both N66 and PP. Significant correlations between NMP polymers were also detected for yellowfin tuna, with most paired comparisons resulting in significant, positive correlations. The strongest associations across the five polymers for yellowfin tuna were observed between N66 – PE (0.81), N66 – PP (0.71), and PE – PP (0.64). PVC was significantly correlated with the same three polymers observed as significant for dolphinfish, but again the strength of the relationships for yellowfin tuna was less than 0.4 for both N66 and PC.

Cross-validated classification success to the three ocean basins based on NMP concentrations (i.e., polymer signatures) was modest at 68% for dolphinfish and 58% for yellowfin tuna. Nevertheless, multivariate NMP means and 95% confidence intervals from CDA were distinct among individuals from the three ocean basins for both dolphinfish and yellowfin tuna (Fig. 3). For dolphinfish, discrimination of Indian Ocean samples was strongly influenced by N66, while discrimination of individuals sampled from the Atlantic and Pacific Oceans was influenced primarily by PE, PVC, and N66. For yellowfin tuna, discrimination of individuals from the Indian Ocean was again influenced strongly by N66. Biplot vectors from CDA showed that separation between individual yellowfin tuna from the Atlantic and Pacific Oceans was primarily influenced by PVC and PE (Fig. 3). Due to the presence of intra-basin variation in NMP signatures, we also ran QDFA models with all regions as the

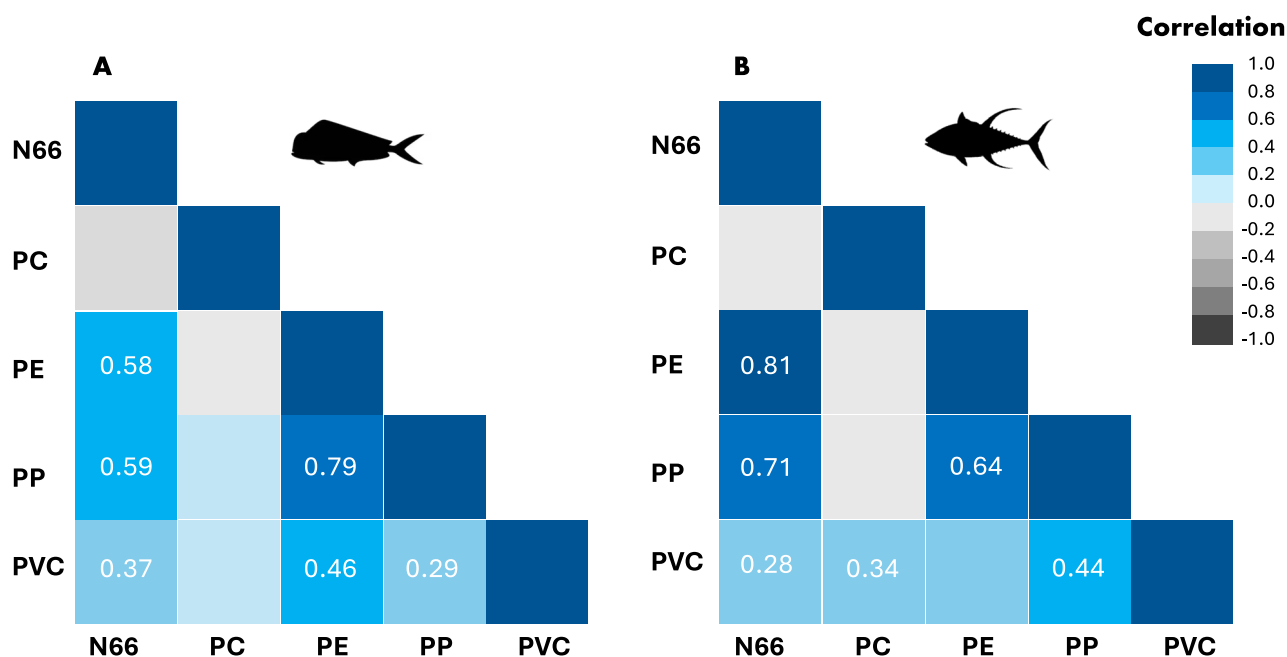


Fig. 2 Correlation matrix for the five primary NMP polymers (PC, PE, PP, PVC, N66) quantified in the muscle tissue of dolphinfish (A) and yellowfin tuna (B). The strength and direction of linear correlation is shown by colors. Darker blue shading associated with stronger, positive correlations. Significant correlations between polymer types are denoted by including values (correlation coefficients) in matrix squares.

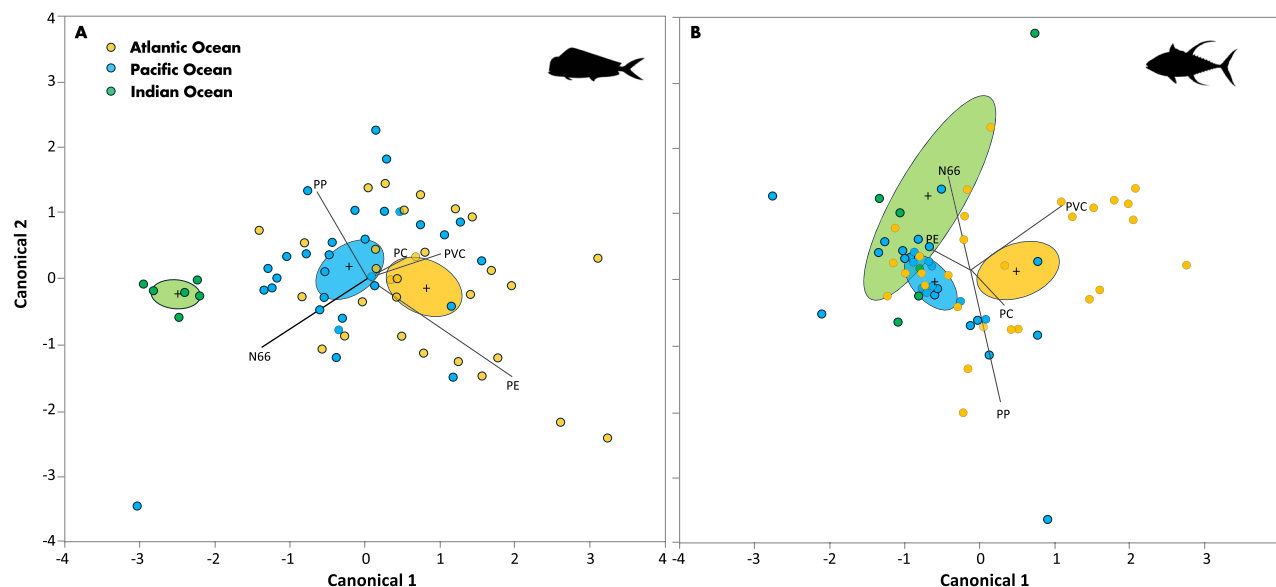


Fig. 3 Canonical discriminant analysis (CDA) plots based on the five primary NMP polymers quantified (PC, PE, PP, PVC, N66) in the muscle tissue of dolphinfish (A), and yellowfin tuna (B) from the Atlantic, Pacific, and Indian Oceans. Ellipses represent 95% confidence limit around each multivariate mean (+) and biplot vectors show the influence of each polymer on ocean-basin discrimination.

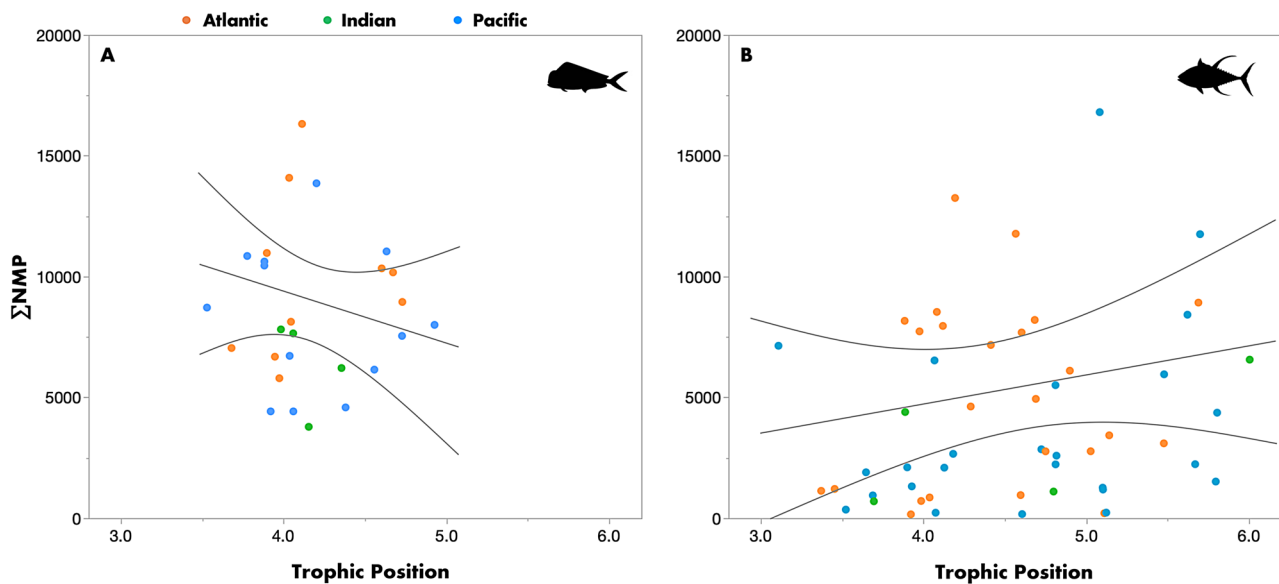


Fig. 4 Relationship between ΣNMP concentrations ($\mu\text{g g}^{-1}$ DW) and trophic position (TP) by ocean basin for dolphinfish (A) and yellowfin tuna (B). Linear regression and 95% confidence intervals shown. Trophic position based on $\delta^{15}\text{N}_{\text{AA}}$ weighted means of select source and trophic amino acids.

grouping factor, and classification success of dolphinfish to each of the 11 regions increased to 89%; however, regional classification dropped to 55% for yellowfin tuna (based on 10 regions).

Trophic position estimates derived from $\delta^{15}\text{N}_{\text{AA}}$ weighted means of select source (glycine, lysine, phenylalanine) and trophic (alanine, glutamic acid, leucine) amino acids indicated relatively consistent trophic position estimates within each species regardless of ocean basin (Fig. 4; Table S5). Mean trophic position for both species in the three oceans was relatively similar: dolphinfish (range: 4.08–4.22) and yellowfin tuna (4.40–4.67), and the extent of observed trophic position estimates of individuals was markedly higher for yellowfin tuna (Fig. 4). ΣNMP concentrations increased in yellowfin with increasing trophic position, with the opposite trend observed for dolphinfish. Nevertheless, in both species the relationship between muscle tissue ΣNMP concentration and trophic position was not significant (F-test $p > 0.05$). Moreover, the trophic position of yellowfin tuna was higher than dolphinfish in nearly all regions examined even though yellowfin tuna displayed lower ΣNMP concentrations.

Discussion

Species-specific variation in ΣNMP concentration was pronounced across regions sampled for the two pelagic fishes, with NMP body burdens elevated relative to other studies of marine fishes. Although studies applying Py-GC-qQq-MS analysis to quantify NMP concentrations in muscle tissue of marine fauna are limited, the approach was applied recently to predatory fishes that inhabit estuarine habitats in the Gulf of Mexico. Average ΣNMP body burdens for red drum (*Sciaenops ocellatus*), spotted seatrout (*Cynoscion nebulosus*) were below $1,000 \mu\text{g g}^{-1}$ DW while ΣNMP concentration in gafftopsail catfish (*Bagre marinus*) was reported at $1,600 \mu\text{g g}^{-1}$ DW³¹. By contrast, observed NMP body burdens of dolphinfish and yellowfin tuna were markedly higher, and sometimes an order of magnitude above reported values for estuarine taxa. Of the two pelagic species examined, the lowest ΣNMP concentrations were observed for yellowfin tuna in the Atlantic and Pacific Oceans with average values across all regions sampled in both oceans at approximately $5,000 \mu\text{g g}^{-1}$ DW. ΣNMP body burdens of dolphinfish were often twofold higher than yellowfin tuna in most regions sampled.

Given the potential value of large pelagic fishes as indicators of microplastic risks in marine ecosystems, several studies have addressed the prevalence of microplastic ingestion in ocean predators using more conventional methods (microscopic quantification of plastics in stomachs), often followed by chemical characterization with spectroscopic analysis³². Findings from microscopic and/or spectroscopic analysis are not directly comparable to our findings due in part to the fact that entry and integration of NMPs in the muscle tissue of pelagic fishes occurs through both the gastrointestinal tract as well as absorption through the gills, with stomach content analysis often biased toward larger microplastics that are likely excreted. Nevertheless, observations from coupled microscopic and spectroscopic analysis provide some useful context for explaining trends observed in the present study. A recent study observed that several microplastic polymers were present in the gastrointestinal tract and gills of dolphinfish, yellowfin tuna, and other pelagic fishes, albeit sample sizes were small³³. Moreover, through the application of microscopic and spectroscopic methods, earlier studies have reported high occurrences of microplastics (~ 80–100% of individuals assayed) for dolphinfish³⁴ and yellowfin tuna²². Our observation of NMPs present in the muscle tissue of 100% of the individuals assessed with Py-GC-qQq-MS aligns well with these studies and suggest that despite being relatively far removed from terrestrial sources of microplastics, large pelagic fishes and associated communities remain vulnerable to NMP contamination in the open ocean.

Region-specific variation in muscle tissue Σ NMP concentrations centered on dolphinfish and yellowfin tuna since both species maintained broad geographic coverage across the regions investigated. Species- and inter-ocean differences in Σ NMP concentrations were evident while intra-basin variation for both species within the Atlantic Ocean or within the Pacific Ocean was more restricted. For example, average Σ NMP concentrations in dolphinfish were comparable in four of the five regions sampled in both the Atlantic Ocean (range: ~14,000–16,000 $\mu\text{g g}^{-1}$ DW) and Pacific Ocean (range: ~ 6,000–10,000 $\mu\text{g g}^{-1}$ DW), indicating that NMP loading or exposure to these CECs may be relatively similar across broad geographic areas within the same ocean, which generally aligns with spatial predictions of plastic concentration at the ocean-basin scale³⁵. Still, within each ocean, Σ NMP concentration in one region was markedly different for dolphinfish relative to the four other regions. While interesting regional trends in NMP body burden emerged from this study for both species, our characterization of NMP concentrations was based on relatively small sample sizes that may not be entirely representative of dolphinfish or yellowfin tuna in a specific area, and limited sample sizes also reduce the statistical power of tests performed to investigate regional trends.

In the Atlantic Ocean, Σ NMP body burdens of dolphinfish from the Gulf of Mexico displayed concentrations more than 50% lower than other regions investigated, while in the Pacific Ocean dolphinfish collected in the Northwest Pacific displayed Σ NMP concentrations nearly twofold higher than any other region sampled in this ocean basin. Similar trends in both the Atlantic and Pacific Oceans were also observed for yellowfin tuna, with Σ NMP body burdens again lowest in the Gulf of Mexico for this species relative to regions in the Atlantic Ocean. Increased Σ NMP concentrations for dolphinfish collected in the Northwest Pacific off Taiwan in the East China Sea is not unexpected and ostensibly linked to higher levels of plastic emission in the western Pacific Ocean, as marine plastics in this region are present at extremely elevated levels³⁶. This includes surface waters off Taiwan and China which are known to be highly enriched in NMPs³⁷, and likely responsible for high levels present in dolphinfish from this region. In contrast, lower Σ NMP body burdens observed for dolphinfish and yellowfin tuna from the Gulf of Mexico relative to other regions in the Atlantic Ocean was unexpected given that microplastics concentrations previously reported in the northern Gulf of Mexico are among the highest in the Atlantic Ocean³⁸. Dolphinfish and yellowfin tuna in the Gulf of Mexico commonly reside in offshore waters associated with a major mesoscale oceanographic feature, the Loop Current. This mesoscale current is a major transport system that brings in warm, oceanic waters from the Caribbean Sea into the Gulf of Mexico. The Loop Current and associated mesoscale features also serve to influence the spatial distribution and alter residency times of contaminants (NMPs) in the northern Gulf of Mexico, which are closely linked to circulation patterns³⁹. It is possible that Loop Current dynamics and associated water mixing serve to alter (i.e., reduce) NMP concentrations in surface waters of the outer shelf and slope where dolphinfish and yellowfin tuna reside.

The occurrence of dominant NMP polymers present in the muscle tissue of the pelagic fishes investigated align with reported abundance of NMP polymers in surface waters of the ocean². For the two species investigated and across nearly all regions, PE was the most abundant polymer type and overall comprised the bulk of all NMPs observed for dolphinfish (62%) and yellowfin tuna (50%) assayed. Findings from a meta-analysis of NMP polymers present in surface waters of the Atlantic and Pacific Oceans indicated that PE was the most prevalent and abundant polymer, accounting for > 50% of total polymer concentration quantified in open ocean waters off the continental shelf². Apart from PE, other primary NMP polymers in dolphinfish and yellowfin tuna, N66 and PP were consistently present in the muscle tissue of both species investigated and across all regions sampled. Again, our results of N66 and PP being moderately abundant in the muscle tissue of these two species are in accord with the relative abundance of these polymers present in surface waters of the Atlantic and Pacific Oceans^{6,39}. Finally, NMP polymers accounting for minor contributions to overall muscle tissue NMP body burdens of dolphinfish and yellowfin tuna, such as PS (< 1.0% of total NMP composition), are also commonly observed at reduced levels (< 5%) in surface waters of the ocean². Overall, our findings suggest that NMP polymers detected in the two pelagic species investigated are generally reflective of main NMP polymer types reported in surface waters of the ocean; however, the lack of paired seawater samples within each region limits our ability to confirm their value as sentinel species for characterizing the abundance and distribution of NMPs in the ocean.

Positive correlations were present between several of the NMP polymers quantified in the tissue of dolphinfish and yellowfin tuna. Significant correlations between PE, PP, and N66 are not surprising since these polymers, both separately and blended, are used in a variety of applications ranging from packaging to fishing applications^{40,41}. For example, PP and PE polymers are commonly blended to make ropes and nets for commercial fishing and shipping operations because blends of mixed fibers increase the strength and durability of certain gear⁴². At the same time, lost gears (e.g., ghost netting) manufactured from PP-PE-N66 blends are a meaningful source of NMP pollution in the ocean⁴³. While correlations were observed among polymer types, regional variation in NMP polymer composition for both dolphinfish and yellowfin tuna was present within and among ocean basins, potentially indicating that NMP signatures in the muscle tissue of these predators may be useful for discriminating individuals from different geographic regions. Chemical tracers in muscle tissue or hard parts (e.g., otoliths) are commonly used to assess the origin, migration ecology, and stock structure of marine fishes^{44–47}, and therefore NMP signatures may also serve as anthropogenic markers for addressing ecological questions related to movements and exposure histories of pelagic fishes and other marine taxa. Nevertheless, additional research on the discriminatory power of NMP signatures among sources (i.e., regions) that includes larger sample sizes and integrates temporal variability is needed to determine the potential usefulness of these chemical markers for addressing population-level questions.

Contaminants have the potential to accumulate and magnify across trophic levels in marine food webs^{48–50}. For microplastics, links to biomagnification in higher trophic level predators are often less evident or inconclusive^{51–53}. Similarly, our findings did not establish a significant relationship between trophic position and NMP body burden for either species investigated. While a positive association was observed between trophic position and Σ NMP concentration for yellowfin tuna, the relationship was not significant and possibly compromised by pooling data across all geographic regions sampled. Moreover, of the two species investigated, trophic position was consistently higher for yellowfin tuna while displaying lower Σ NMP body burdens relative to dolphinfish. The apparent mismatch between trophic position and Σ NMP body burden between the two species may be related to differences in foraging behaviors, which result in these species exploiting prey fields differently. Dolphinfish feed almost exclusively on fishes and invertebrates in near surface waters, often displaying nondiscriminatory foraging behaviors with Sargassum and plastic debris often present in their stomachs^{54,55}. In contrast, yellowfin tuna feed in surface waters but also dive hundreds of meters to actively feed on a variety of deepwater prey in the mesopelagic zone^{56–58}. Since concentrations of microplastics in seawater, including the specific polymer (i.e., PE) that made up the bulk of NMPs in the muscle tissue of both species, often peak in surface waters^{6,39}, it is plausible to assume that dolphinfish experience significantly higher exposure to NMPs by foraging on prey that inhabit surface waters. Yellowfin tuna exposure to NMPs may be moderated to some degree by feeding on

deepwater prey in the mesopelagic zone with potentially lower associated NMP body burdens; however, differences in age, size, and life history between the two species are also contributing factors.

Inter-ocean variation in mean trophic position based on CSIA-AA was generally negligible for both species investigated. Differences were often only about 0.2 trophic steps among species-specific means for each of the three oceans for both dolphinfish and yellowfin tuna, suggesting these species play similar functional roles in pelagic food webs regardless of location. Similarly, intra-ocean variation in trophic position was relatively minor for dolphinfish and yellowfin tuna sampled from five regions in both the Atlantic and Pacific Ocean. For example, despite sampling dolphinfish from different regions in the Atlantic Ocean that vary greatly in biological and physicochemical conditions, estimated trophic position was highly similar among the five regions (~4.0, 4.1, 4.1, 4.1, 4.2), supporting the premise of this species fulfills similar trophic roles throughout the Atlantic Ocean. Our trophic position estimates are in accord with previous studies applying CSIA-AA based approach to estimate trophic position of pelagic species such as dolphinfish and tunas³⁰. Moreover, a recent study reported similar trophic position estimates for dolphinfish collected in different ocean basins using a similar CSIA-AA approach⁵⁹, while trophic position estimates derived for yellowfin tuna using other dietary tracers have also reported comparable values across different geographic regions⁶⁰. As a result, geographic differences in NMP concentrations observed for the species investigated are likely related to ambient NMP conditions rather than region-specific shifts in foraging strategies by these taxa.

This study serves as the first comprehensive investigation of NMP body burdens in the muscle tissue of higher order consumers in pelagic ecosystems across multiple regions and oceans. The two species investigated are highly migratory with ranges that encompass large expanses of oceans^{61–63}. As a result, NMP body burdens in the muscle tissue of these predators may serve as useful indicators of NMP conditions in the waters they inhabit, although paired seawater samples are required in future investigation to establish a direct link between NMP ambient conditions and muscle tissue values of these predators. Findings from our study clearly indicate that NMPs are persistent in higher-order predators in the Atlantic, Indian, and Pacific Oceans, and will serve as baselines for future investigations of NMP exposure of pelagic predators.

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Data availability All data needed to evaluate conclusions of the paper are present in the paper and/or Supplementary Information. Raw data (% lipid, NMP concentrations of all polymer types, and CSIA-AA per individual fish) available upon request.

Declarations

Competing interests The authors declare no competing interests.

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References

1. De Souza Machado, A. A., Kloas, W., Zarfl, C. & Hempel Rillig, M. C. Microplastics as an emerging threat to terrestrial ecosystems. *Glob Chang. Biol.* **24**, 1405–1416 (2018).
2. Erni-Cassola, G., Zadjelovic, V., Gibson, M. I. & Christie-Oleza, J. A. Distribution of plastic polymer types in the marine environment; A meta-analysis. *J. Hazard. Mater.* **369**, 691–698 (2019).
3. Kershaw, P. J. & Rochman, C. M. Sources, fate and effects of microplastics in the marine environment: part two of a global assessment. Reports and studies-IMO/FAO/Unesco-IOC/WMO/IAEA/UN/UNEP joint group of experts on the scientific aspects of marine environmental protection (GESAMP) Eng No. 93, 220 (2016).
4. Lebreton, L. et al. River plastic emissions to the world's oceans. *Nat. Commun.* **8**, 15611 (2017).
5. Schmidt, C., Krauth, T. & Wagner, S. Export of plastic debris by rivers into the sea. *Environ. Sci. Tech.* **51**, 12246–12253 (2017).
6. Pabortsava, K. & Lampitt, R. S. High concentrations of plastic hidden beneath the surface of the Atlantic Ocean. *Nat. Commun.* **11**, 4073 (2020).
7. Dimassi, S. N. et al. Degradation-fragmentation of marine plastic waste and their environmental implications: A critical review. *Arab. J. Chem.* **15**, 104262 (2022).
8. Lambert, S. & Wagner, M. Microplastics are contaminants of emerging concern in freshwater environments: an overview. In *Freshwater Microplastics. The Handbook of Environmental Chemistry* vol. 58 (eds Wagner, M. & Lambert, S.) (Springer, Cham, 2018).
9. Stapleton, M. J. & Hai, F. I. Microplastics as an emerging contaminant of concern to our environment: a brief overview of the sources and implications. *Bioengineered* **14**, 2244754 (2023).
10. Coyle, R., Hardiman, G. & O'Driscoll, K. Microplastics in the marine environment: A review of their sources, distribution processes, uptake and exchange in ecosystems. *Case Stud. Chem. Environ. Eng.* **2**, 100010 (2020).
11. Mao, Y. et al. Phytoplankton response to polystyrene microplastics: Perspective from an entire growth period. *Chemosphere* **208**, 59–68 (2018).
12. Hitchcock, J. N. Microplastics can alter phytoplankton community composition. *Sci. Total Environ.* **1**, 819:153074 (2022).
13. Botterell, Z. L. R. et al. Bioavailability and effects of microplastics on marine zooplankton: A review. *Environ. Pollut.* **245**, 98–110 (2019).
14. Monclús, L. et al. Mapping the chemical complexity of plastics. *Nature* **643**, 349–355 (2025).
15. Soltanighias, T., Umar, A., Abdullahi, M., Abdallah, M. A. & Orsini, L. Combined toxicity of perfluoroalkyl substances and microplastics on the sentinel species *Daphnia magna*: Implications for freshwater ecosystems. *Environ. Pollut.* **363**, 125133 (2024).
16. Sethia, P., Nandhini, D. & Amutha, S. Effects of marine microplastic on marine life and the food webs—A detailed review. *Mar. Ecol.* **45**, e12819 (2024).
17. Malinowski, C. R., Searle, C. L., Schaber, J. & Höök, T. O. Microplastics impact simple aquatic food web dynamics through reduced zooplankton feeding and potentially releasing algae from consumer control. *Sci. Total Environ.* **904**, 166691 (2023).
18. Akhbarizadeh, R., Moore, F. & Keshavarzi, B. Investigating microplastics bioaccumulation and biomagnification in seafood from the Persian Gulf: a threat to human health? *Food Addit. Contam. Part. Chem. Anal. Control Expo Risk Assess.* **36**, 1696–1708 (2019).
19. Parolini, M. & Romano, A. Geographical and ecological factors affect microplastic body burden in marine fish at global scale. *Environ. Pollut.* **352**, 124121 (2024).

20. Barceló, D., Picó, Y., Alfaran, A. H. & Microplastics Detection in human samples, cell line studies, and health impacts. *Environ. Toxicol. Pharm.* **101**, 104204 (2023).
21. Galloway, T., Cole, M. & Lewis, C. Interactions of microplastic debris throughout the marine ecosystem. *Nat. Ecol. Evol.* **1**, 0116 (2017).
22. Justino, A. K. S. et al. From prey to predators: Evidence of microplastic trophic transfer in tuna and large pelagic species in the southwestern Tropical Atlantic. *Environ. Pollut.* **327**, 121532 (2023).
23. Huang, W. et al. Microplastics and associated contaminants in the aquatic environment: A review on their ecotoxicological effects, trophic transfer, and potential impacts to human health. *J. Hazard. Mater.* **405**, 124187 (2021).
24. Li, Y. et al. Potential health impact of microplastics: A review of environmental distribution, human exposure, and toxic effects. *Environ. Health* **1**, 249–257 (2023).
25. Persiani, E. et al. Microplastics: a matter of the heart (and vascular system). *Biomedicines* **11**, 264 (2023).
26. Gahn, M. B. et al. Rapid and sensitive quantification of nano- and microplastics in water, sediment, and biological tissue by pyrolysis-gas chromatography tandem mass spectrometry with dynamic reaction monitoring. *Analyt Chem.* **98**, 633–641 (2026).
27. Monikh, F. A. et al. Challenges in studying microplastics in human brain. *Nat. Med.* **31**, 4034–4035 (2025).
28. Rauert, C. et al. Assessing the efficacy of pyrolysis-gas chromatography-mass spectrometry for nanoplastic and microplastic analysis in human blood. *Environ. Sci. Technol.* **59**, 1984–1994 (2025).
29. Nielsen, J. M., Popp, B. N. & Winder, M. Meta-analysis of amino acid stable nitrogen isotope ratios for estimating trophic position in marine organisms. *Oecologia* **178**, 631–642 (2015).
30. Bradley, C. J. et al. Trophic position estimates of marine teleosts using amino acid compound specific isotopic analysis. *Limnol. Oceanogr. Methods.* **13**, 476–493 (2015).
31. Mortuza, A. et al. Comparing persistent (polycyclic aromatic hydrocarbons and polychlorinated biphenyls) and emerging nano(micro)plastics (NMPs) pollutant body-burdens in oysters and fish from Matagorda Bay (Texas, USA). *Mar. Pollut Bull.* **221**, 118495 (2025).
32. Torresi, M. et al. Microplastic characterization in the stomachs of swordfish (*Xiphias gladius*) from the western Mediterranean Sea. *Mar. Pollut Bull.* **206**, 116767 (2024).
33. Pereira, R. et al. Microplastic contamination in large migratory fishes collected in the open Atlantic Ocean. *Mar. Pollut Bull.* **186**, 114454 (2023).
34. Li, W. et al. Microplastics in a pelagic dolphinfish (*Coryphaena hippurus*) from the eastern pacific ocean and the implications for fish health. *Sci. Total Environ.* **809**, 151126 (2022).
35. Kaandorp, M. L. A., Lobelle, D., Kehl, C., Dijkstra, H. A. & van Sebille, E. Global mass of buoyant marine plastics dominated by large long-lived debris. *Nat. Geosci.* **16**, 689–694 (2023).
36. Kvale, K., Prowe, A. E. F., Chien, C. T., Landolfi, A. & Oschlies, A. The global biological microplastic particle sink. *Sci. Rep.* **10**, 16670 (2020).
37. Jambeck, J. R. et al. Plastic waste inputs from land into the ocean. *Science* **347**, 768–771 (2015).
38. Di Mauro, R., Matthew, J. K. & Benfield, M. C. Abundant plankton-sized microplastic particles in shelf waters of the northern Gulf of Mexico. *Environ. Pollut.* **230**, 798–809 (2017).
39. Zhou, X., Xiao, S., Ramirez, M. & Bracco, A. Modeling river and urban related microplastic pollution off the southern United States. *Emerg. Contam.* **1**, 9 (2025).
40. Graziano, A., Jaffer, A. & Sain, M. Review on modification strategies of polyethylene/polypropylene immiscible thermoplastic polymer blends for enhancing their mechanical behavior. *J. Elastom Plast.* **51**, 009524431878380 (2018).
41. Hossain, M. T. et al. Research and application of polypropylene: a review. *Discover Nano.* **19**, 2 (2024).
42. Juan, R., Paredes, B. & Garcia-Munoz, D. C. Quantification of PP contamination in recycled PE by TREF analysis for improved the quality and circularity of plastics. *Polym. Test.* **100**, 107273 (2021).
43. Wataniyakun, W., Gall, M. L., Rakwe, M. E., Karl, C. W. & Larsen, R. B. Biodegradable fishing gears: A potential solution to ghost fishing and marine plastic pollution. *Mar. Pollut Bull.* **212**, 117607 (2025).
44. Rooker, J. R. et al. Natal homing and connectivity in Atlantic bluefin tuna populations. *Science* **322**, 742–744 (2008).
45. Madigan, D. L. et al. Reconstructing transoceanic migration behaviors of Pacific bluefin tuna using a chemical tracer toolbox. *Ecology* **95**, 1674–1683 (2014).
46. Graves, J. E. et al. Transatlantic movements of juvenile Atlantic bluefin tuna inferred from analyses of organochlorine tracers. *Can. J. Fish. Aquat. Sci.* **72**, 625–633 (2015).
47. Rooker, J. R. et al. Nursery origin of yellowfin tuna in the western Atlantic Ocean: significance of Caribbean Sea and trans-Atlantic migrants. *Sci. Rep.* **13**, 16277 (2023).
48. Cai, Y., Rooker, J. R., Gill, G. & Turner, J. P. Bioaccumulation of mercury in pelagic fishes from the Gulf of Mexico: evaluating links to dietary history and trophic position using stable isotopes and fatty acids. *Can. J. Fish. Aquat. Sci.* **64**, 458–469 (2007).
49. Kljakovic-Gaspic, Z. & Ticina, V. Mercury and selenium levels in archive samples of wild Atlantic bluefin tuna from the Mediterranean Sea. *Chemosphere* **284**, 131402 (2021).

50. Cheng, H. et al. Bioaccumulation and biomagnification of emerging poly-and perfluoroalkyl substances in marine organisms. *Sci. Total Environ.* **851**, 158117 (2022).
51. Miller, M. E., Hamann, M. & Kroon, F. J. Bioaccumulation and biomagnification of microplastics in marine organisms: A review and meta-analysis of current data. *PLoS One.* **15**, e0240792 (2020).
52. Covernton, G. A. et al. Increasing microplastic exposure had minimal effects on fatty acid composition in zooplankton and yellow perch in a large, in-lake mesocosm experiment. *Can. J. Fish. Aquat. Sci.* **81**, 1717–1727 (2024).
53. Gao, S. et al. The bio-accumulation and -magnification of microplastics under predator–prey isotopic relationships. *J. Hazard. Mater.* **480**, 135896 (2024).
54. Rudershausen, P. J. et al. Feeding ecology of blue marlins, dolphinfish, yellowfin tuna, and wahoos from the North Atlantic Ocean and comparisons with other ocean. *Trans. Amer. Fish. Soc.* **139**, 1335–1359 (2010).
55. Brewton, R. A., Ajemian, M. J., Young, P. C. & Stunz, G. W. Feeding ecology of dolphinfish in the western gulf of Mexico. *Trans. Am. Fish. Soc.* **145** (4), 839–853 (2016).
56. Hoolihan, J. P. et al. Vertical and horizontal movements of yellowfin tuna (*Thunnus albacares*) in the Gulf of Mexico. *Mar. Coast Fish.* **6**, 211–222 (2014).
57. Duffy, L. M. et al. Global trophic ecology of yellowfin, bigeye, and albacore tunas: Understanding predation on micronekton communities at ocean-basin scales. *Deep Sea Res. Part. II: Topical Stud. Oceanogr.* **140**, 55–73 (2017).
58. Willis, C. et al. Evaluating the importance of mesopelagic prey to three top teleost predators in the northwest Atlantic Ocean. *ICES J. Mar. Sci.* **82** (3), fsaf028 (2025).
59. Prouse, A. *Trophic ecology and contamination body burden of marine predators across ocean basins. Ph.D. Dissertation* (Texas A&M University, 2025).
60. Popp, B. N. et al. Insight into the trophic ecology of yellowfin tuna, *Thunnus albacares*, from compound-specific nitrogen isotope analysis of proteinaceous amino acids. *Terr. Ecol.* **1**, 173–190 (2007).
61. Block, B. A. et al. Tracking apex marine predator movements in a dynamic ocean. *Nature* **475**, 86–90 (2011).
62. Merten, W., Appeldoorn, R. & Hammond, D. Movement dynamics of dolphinfish (*Coryphaena hippurus*) in the northeastern Caribbean Sea: Evidence of seasonal re-entry into domestic and international fisheries throughout the western central Atlantic. *Fish. Res.* **175**, 24–34 (2016).
63. Rooker, J. R. et al. Population connectivity of pelagic megafauna in the Cuba-Mexico-United States triangle. *Sci. Rep.* **9**, 1663 (2019).

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