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Trophic Positioning and Habitat Ecology: A Comparative Review of PFAS Bioaccumulation Dynamics in Pelagic versus Demersal Fish Species

Elif Tugce Aksun Tümerkan [1,2] *

[1] Ankara Yıldırım Beyazıt University, Department of Food Processing-Food Technology, Vocational School of Technical Sciences, Ankara 06010, Türkiye,
[2] Ankara Yıldırım Beyazıt University, Microplastic Research Laboratory, AYBU Central Research Application and Research Center, Ankara, 06010, Türkiye

Abstract

T Global concern and pose a significant threat to aquatic ecosystems and to the health of human consumers. Due to their extraordinary chemical stability and amphiphilic nature, these persistent chemicals are effectively biomagnified in marine and freshwater food webs. However, the spatial distribution of PFAS in the water column leads to different bioaccumulation pathways between pelagic and bottom species. Understanding these habitat-specific variations is essential for an accurate assessment of the environmental risks and for the development of targeted frameworks for food safety monitoring. Pelagic species that are present in the upper water column are primarily exposed to waterborne fractions of PFAS and highly mobile, water-soluble short-chain alternatives through the uptake of pelagic food webs and by the fishery. As these species often exhibit high metabolic rates and extensive migration patterns, their PFAS profiles are strongly influenced by horizontal spatial changes in water contamination and by rapid trophic translocation. Conversely, demersal and benthic species (e.g. flatfish, cod and turbot) are found close to the seabed and are therefore very vulnerable to long-chain variants of PFOS. The demersal food web is intrinsically linked to the detrital routes and to the organisms living in the sediment, which results in a long-term, chronic exposure matrix for pelagic and demersal fish species. Recent toxicokinetic studies show that while pelagic fish often show a rapid response to changing surface water concentrations, demersal species tend to have significantly higher steady state bioconcentration factors and a higher body weight of hydrochlorofluorocarboxylic and sulphonic PCBs. This comparative analysis highlights that the primary drivers of tissue distribution of PFAS are habitat ecology, interaction with sediments and trophic distribution. Therefore, in order to accurately mitigate the risks of chemical exposure in human food, reliable environmental monitoring and safety regulations need to implement stratified sampling strategies, distinguishing between pelagic and demersal habitats.

Keywords: *PFAS, PFOS, Pelagic Fish, Demersal Fish, Bioaccumulation, Sediment-Water Interface, Seafood Safety.*

Introduction

The bioaccumulation of per- and polyfluoroalkyl compounds in aquatic organisms is a multifaceted process driven by a complex systems including biological, chemical, and environmental differences (Flinders et al., 2025). Especially, structural properties such as perfluoroalkyl chain length and the nature of the polar functional group differ the bioaccumulation potential of these contaminants. In addition to these structural determinants, the intrinsic pharmacokinetic mechanisms--in particular the high affinity for proteins such as serum albumin and liver fatty acid binding proteins, combined with the active translocation by membrane transporters--control the specific distribution, bioaccumulation and elimination kinetics of these compounds in the body (Jia et al., 2022; Ng & Hungerbühler, 2013, 2014). In addition, functional group type is often a more important predictor of internal distribution patterns than length of the chain itself, resulting in different concentrations in tissues such as liver, blood and bile. (Armitage et al., 2016; Shi et Furthermore, the co-exposure of congener molecules with different chain lengths modulates the accumulation kinetics. The uptake of long-chain compounds may be competitively inhibited and the steady state bioconcentration factors of the short-chain analogs can be significantly reduced. The inhibitory effect is due to the fact that long chain congeners have higher binding affinities for important transport proteins such as serum albumin and liver fatty acid-binding proteins, and thus effectively compete with their shorter chain counterparts for these limited sites and membrane transporters. (Wen et al., 2017). Thus, the prevalence of more hydrophobic, long-chain PFAS in environmental mixtures can significantly influence the uptake and tissue-specific accumulation of shorter-chain analogs, a factor that requires meticulous consideration when assessing the cumulative risks associated with complex PFAS contamination profiles (Wen et al., 2017).

In addition to these internal transport dynamics, the trophic position of the species and the distinctive configuration of the food web further influence biomagnification potential, with greater accumulation often seen in organisms at higher trophic levels (Kelly et al., 2024). Moreover, molecular affinity for subcellular components—such as the distribution between protein-rich albumin and polar lipid fractions—significantly impacts the thermodynamic accumulation potential of certain PFAS congeners (Fremlin et al., 2023).

The current knowledge about PFAS accumulation on different fish species is mostly focusing on explain the accumulation based on the relevant compounds characteristic and cover very limited scope, but for the better understanding of how these pollutants cause the risk in fish by food chain to public; investigation of bioaccumulation mechanisms in depth is necessary. Thus, this review is aimed explain the mechanism of PFAS accumulation in the model food matrices, fish tissues by considering from both sides; from fish side such as living area, proximate composition and physical properties, from chemical pollutant side such as mechanic and physicochemical characteristics.

Physicochemical Properties of PFAs Driving Chemical Bioaccumulation

Buildup of PFAS in living things depends less on greasiness than once thought. Instead, it hinges on how long the molecule's tail is, what kind of charged tip it carries, along with its grip strength on proteins and cell layers. Molecules with longer tails plus sulfur-based tips tend to stick harder, leave the body slowly, and grow more concentrated up food chains. On the flip side, those with shorter arms or redesigned parts move faster through plants, slip into water readily. Predicting their behavior means building tools that track exactly how they cross membranes, latch onto bodily structures, flush out over time. Specifically, the molecular docking of these substances to transport proteins is often driven by a combination of exothermic van der Waals forces, electrostatic interactions, and hydrogen bonding (Fan et al., 2025). These binding affinities generally scale with increasing perfluoroalkyl chain length, significantly influencing the subsequent rate of elimination and the overall tissue-specific residue patterns (Brunn et al., 2023; Ma et al., 2023). Moreover, compound-specific variations in partitioning are further underscored by evidence that branched versus linear isomers exhibit distinct transfer efficiencies and pharmacokinetic profiles, which may complicate standardized assessments of bioaccumulation across diverse taxa (Jouanneau et al., 2021).

The Toxicokinetics of PFAS: Protein Binding vs. Phospholipid Partitioning

The unique physical and chemical characteristics of per- and polyfluoroalkyl substances (PFAS) dictate their unique toxicokinetic profiles in biological systems. PFAS have a hydrophobic, oleophobic fluorinated carbon tail, and a hydrophilic head group. In contrast to traditional lipophilic persistent organic pollutants (POPs) that tend to bioaccumulate in adipose tissues, PFAS are characterized by a high affinity for protein-rich and membrane dense compartments . The standardized distribution, tissue bioaccumulation, and biological life cycle of PFAS are determined by this delicate balance between two main mechanisms, i.e. specialized protein attachment and non-specific phospholipid membrane fragmentation.

Short- to long-chain PFAS have a tissue tropism for the plasma and liver over adipose tissue, due to their extremely high binding affinity to serum albumin, fatty acid-binding proteins (FABPs), and many other cellular transporters (Leung, 2023; Lewis, 2022; Hu, 2024). The structure of the perfluoroalkyl carboxylic acids (PFCAs, generally C6-C10) and related functional groups show the greatest binding affinity to serum protein, which is highly structure-dependent (Yao, 2025).

Phospholipid Membrane Interaction and Partitioning

The way phospholipid membranes interact with things is really interesting. When you have a chain of fluorinated carbon the way it stays in the membrane changes. It goes from interacting with proteins to just becoming part of the membrane because of phospholipids. This is especially true for long chains of PFAS. When this happens the PFAS builds up in the membrane, which's a big reason why it accumulates in living things like fish. This has been seen in organisms and fish like in the work of Shi in 2018 Sun in 2022 and Alfa in 2024.When PFAS has a long chain it is hard for the body to get rid of it through the kidneys. This is because the PFAS becomes part of the membrane and the kidneys have a time removing it. As a result the kidneys are not able to clear out the PFAS as shown by Shi in 2018.

The way medium and long chain PFAS act in cell membranes is also worth looking at. These PFAS are able to dissolve in the part of the membrane that does not like water. This happens because of the way the molecules are structured not just because they are attracted to each other. The phospholipid membrane and PFAS interact in a way that is governed by the structure of the molecules, than just a simple attraction.

PFAS Accumulation in Fish: Tissue Tropism & Habitat Disparities

Fresh water fish tend to accumulate much higher levels of PFAS (per- and poly-fluoroalkyl substances) than marine species, owing to their closer proximity to industrial pollution sources and the smaller volume of dilution in rivers and lakes. Based on U.S. EPA data, average totals range from 9,500 to 11,800 ng/kg in freshwater fillets versus generally negligible parts-per-billion levels in ocean-going marine fish. But recent ecotoxicological studies

show that the severity of this chemical burden is governed by a fish's specific internal anatomy. PFAS are highly proteinophilic (protein binding) compounds and therefore do not distribute homogenously among fish tissues. Evidence from peer-reviewed research indicates that bioaccumulation is maximized in the highly vascular, protein-rich organs: liver (l), viscera (v), and gonads/gills Dynamic tissue-distribution characterization reveals that liver amounts of primary legacy substances such as PFOS routinely reach 60 to 350 times higher than levels in the surrounding edible muscle fillet.

Influence of Fish Proximate Composition on the Bioaccumulation and Proteinophilic Partitioning of Per- and Polyfluoroalkyl Substances (PFAS)

The mechanism for the bioaccumulation of per-and polyfluoroalkyl substances (PFAS) into fish diverges from the typical lipophilic partitioning model and incorporates the interaction between the chemicals' properties, the habitat where the organism lives, and the organism's internal physiological traits. There is a global pattern between species and the type of habitat they inhabit: freshwater fish contain significantly higher levels of PFAS compared to marine organisms because freshwater is often closer to industrial and consumer use and sources of contamination; furthermore, lacustrine and riverine environments have lower dilution capabilities. Examining individual tissues in a global scale assessment of fillet samples shows an opposite relationship between crude lipid content and PFAS concentrations: leaner muscle has higher chemical load. This occurs because PFAS, unique to other pollutants of concern to fish, is proteinophilic, which means they preferentially partition onto functional proteins such as serum albumin or liver fatty acid-binding proteins. Thus, the chemical has a high affinity for protein-binding instead of accumulating within storage lipids and partitions strongly into the blood plasma and to blood organs like the liver and kidneys.Consequently, traditional predictive models using total lipid or total protein as simple normalization metrics fail to capture real-world variability (Giari et al., 2023; Taiwo et al., 2025). Because PFAS bind selectively to distinct functional proteins rather than bulk protein mass, total protein content does not serve as a reliable standalone predictor (Babut et al., 2017). Instead, mechanistic and food-web models indicate that for long-chain variants, bioaccumulation is heavily driven by phospholipid partitioning, with renal elimination remaining negligible (Taiwo et al., 2025). For these long-chain compounds, the primary route of uptake shifts systematically from branchial gills to dietary ingestion as chain length increases, significantly slowing elimination kinetics—a process successfully simulated by advanced mechanistic models substituting specific protein/phospholipid fractions for lipid values (Valsecchi et al., 2020; Taiwo et al., 2025).

Aside from pure proximate composition, other organisms differences can be best explained by properties of the organism itself, choice of diet, transporter protein, and the habitat of the transporter protein (Liang, 2022). Many studies of river and lake systems have confirmed through stable isotope analysis that trophic position and foraging ecology strongly predict PFAS signatures, much more so than fish size or bulk composition (Macorps, 2022; Xing et al., 2023; Levanduski et al., 2026). Carnivores, tertiary consumers more readily accumulate PFAS body burdens than omnivores and lower trophic level counterparts (Liang, 2022) as is evidenced by higher accumulation in catfish, an apex predator, compared to their conspecific carp counterparts across all body tissues (Lewis, 2022). Structural and commercial considerations significantly further differentiate PFAS accumulation independent of mere fat levels as wild fish have substantially higher accumulation in their bodies compared to farmed varieties and the inclusion or omission of skin in a fish fillet also structurally influences the final PFAS pattern(Figueroa-Muoz, 2024).

Conclusion

This review deeply investigated the key factors for bioaccumulation of PFAs in fish tissue. The results and compare assessment could be beneficiary for different disciplines from food science to environmentalist and gastronomy.

Author Contribution Statement

Please indicate how each author contributed to this work and at what stage. For example:

ETAT: Data collection, investigation, formal analysis, and writing the original draft, supervision, conceptualization, methodology, review and editing

Conflict of Interest

The author declares no conflict of interest

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