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**BIOACUMULAÇÃO DE METAIS E METALOIDES EM CAVALA-DA-ÍNDIA E
ATUM-AMARELO (SCOMBRIDAE) NO ARQUIPÉLAGO DE SÃO PEDRO E
SÃO PAULO, BRASIL**

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Dissertação apresentada para o Programa de Pós-graduação em Ciência e Tecnologia Ambiental da Universidade Federal da Fronteira Sul (UFFS), como um dos requisitos para obtenção do título de Mestra em Ciência e Tecnologia Ambiental.

Orientador: Prof. Dr. Daniel Galiano

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SUMÁRIO

INTRODUÇÃO GERAL	5
Capítulo 1: Contaminação por metais e metaloides em <i>Acanthocybium solandri</i> e <i>Thunnus albacares</i>: uma análise bibliométrica (1973 – 2026)	7
1. INTRODUÇÃO	9
2. METODOLOGIA	12
3. RESULTADOS E DISCUSSÃO.....	13
3.1 TENDÊNCIA ANUAL DAS PUBLICAÇÕES	13
3.2 PRINCIPAIS PERIÓDICOS DE PUBLICAÇÕES	15
3.3 PRINCIPAIS AFILIAÇÕES EM PESQUISA	16
3.4 PAÍSES MAIS RELEVANTES.....	17
3.5 CONTRIBUIÇÕES DOS AUTORES	18
3.6 ANÁLISE DE PALAVRAS-CHAVE	19
4. CONSIDERAÇÕES FINAIS	22
Capítulo 2: Bioaccumulation of metals and metalloids in Yellowfin tuna and Wahoo (Scombridae) in the Saint Peter and Saint Paul Archipelago, Brazil	28
1 INTRODUCTION.....	29
2 MATERIALS AND METHODS.....	33
2.1 STUDY AREA.....	33
2.2 DATA COLLECTION.....	34
2.3 SAMPLE PREPARATION	34
2.4 DATA ANALYSIS.....	35
2.5 HUMAN HEALTH RISK ASSESSMENT	35
3 RESULTS	37
4 DISCUSSION	41
ACKNOWLEDGMENTS.....	47
CONSIDERAÇÕES FINAIS	57

INTRODUÇÃO GERAL

Os oceanos acumulam, há décadas, quantidades crescentes de metais e metalóides oriundos de fontes naturais e antropogênicas. Ao contrário dos contaminantes orgânicos, esses elementos não se degradam: redistribuem-se continuamente entre a água, o sedimento e os organismos vivos (Tchounwou et al., 2012; Ali et al., 2019), atravessando cadeias alimentares inteiras por meio da bioacumulação e da biomagnificação (Gao et al., 2021; Ray e Vashishth, 2024). Grandes predadores pelágicos são os que mais concentram esse acúmulo — seus tecidos integram anos de exposição e funcionam, na prática, como registros da qualidade ambiental dos oceanos em escala regional e global (Gao et al., 2021; Bi et al., 2026).

O problema ganha outra dimensão quando se considera que o pescado é uma das principais fontes de proteína animal no mundo, e que seu consumo cresce consistentemente ano a ano (FAO, 2024). Isso significa que as concentrações de metais presentes no músculo de espécies comerciais chegam, inevitavelmente, à mesa das pessoas — tornando a relação entre contaminação ambiental e saúde pública cada vez mais urgente (Castro-González e Méndez-Armenta, 2008; Rahman et al., 2026). A magnitude dessa exposição depende de fatores como o nível trófico das espécies, sua longevidade e comportamento migratório, bem como as propriedades físico-químicas de cada elemento (Liu et al., 2026; Wang et al., 2026).

A cavala-da-índia (*Acanthocybium solandri*, Cuvier, 1832) e o atum-amarelo (*Thunnus albacares*, Bonnaterre, 1788) são dois exemplos de predadores de topo de cadeia com alta relevância comercial e ecológica. Amplamente distribuídas nas águas tropicais e subtropicais dos oceanos Atlântico, Índico e Pacífico, ambas as espécies são altamente migratórias e se alimentam principalmente de peixes, cefalópodes e crustáceos (Júnior et al., 2003; Baque-Menoscal et al., 2012; Martins et al., 2024) — uma dieta que as expõe de forma contínua aos contaminantes acumulados nos níveis inferiores da cadeia trófica (Shipley et al., 2019). O atum-amarelo responde por cerca de 25–30% das capturas mundiais de atuns, ultrapassando 1,5 milhão de toneladas anuais (FAO, 2024), enquanto a cavala-da-índia, embora menos representada nas frotas industriais, é explorada comercialmente em diversas regiões tropicais e subtropicais (Collette e Nauen, 1983; Gao et al., 2020). Pela posição que ocupam na cadeia alimentar e pela extensão de suas rotas migratórias, essas espécies constituem indicadores relevantes da contaminação oceânica

— e representam, ao mesmo tempo, um risco potencial para quem as consome regularmente.

O Arquipélago de São Pedro e São Paulo (ASPSP) surge nesse contexto como uma área de investigação de grande interesse. Situado a cerca de 1.100 km da costa nordeste do Brasil (Campos et al., 2010), é um dos arquipélagos mais remotos e menores do mundo, mas de relevância ecológica e estratégica inegável: abriga alta biodiversidade marinha (Pinheiro et al., 2020), serve como área de alimentação para *T. albacares* e *A. solandri* (Vaske-Jr. et al., 2005) e concentra estoques pesqueiros monitorados há mais de uma década (Viana et al., 2015). O fato de estudos anteriores terem detectado poluentes orgânicos persistentes em organismos do arquipélago (Dias et al., 2013; Oliveira-Ferreira et al., 2026) deixa claro que o isolamento geográfico não equivale à ausência de contaminação. As concentrações de metais e metaloides nas espécies pescadas na região, porém, ainda não haviam sido investigadas.

A presente dissertação foi organizada em dois capítulos que se complementam. O Capítulo 1 mapeia, por meio de análise bibliométrica, a evolução da produção científica global sobre contaminação por metais e metaloides em *A. solandri* e *T. albacares* entre 1973 e 2026. Os dados foram extraídos das bases Scopus e Web of Science e analisados com o pacote Bibliometrix no ambiente R, permitindo identificar tendências temporais, periódicos de maior impacto, países e instituições mais produtivos, redes de colaboração e a estrutura temática do campo (Donthu et al., 2021). Um dos achados mais expressivos foi a marcada sub-representação de *A. solandri* na literatura, reflexo de sua menor presença nos programas internacionais de monitoramento (Zischke, 2012; Kindong et al., 2022). O Capítulo 2 parte exatamente dessa lacuna para apresentar dados empíricos originais: concentrações de 14 elementos (Ag, Al, As, Ba, Cd, Cr, Cu, Fe, Li, Mn, Hg, Pb, Se e Zn) foram quantificadas no tecido muscular das duas espécies coletadas no ASPSP. A análise incluiu comparações interespecíficas, correlações com o comprimento corporal, verificação de conformidade com os limites estabelecidos pela ANVISA, OMS e pela EFSA, e avaliação do risco à saúde humana com base na metodologia da USEPA (2000).

Capítulo 1: Contaminação por metais e metaloides em *Acanthocybium solandri* e *Thunnus albacares*: uma análise bibliométrica (1973 – 2026)

Metal and Metalloid Contamination in *Acanthocybium solandri* and *Thunnus albacares*: A Bibliometric Analysis (1973–2026)

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RESUMO

A contaminação por metais e metaloides em peixes marinhos de alto nível trófico tem se consolidado como uma preocupação na interface entre ecotoxicologia e saúde pública. Nesse contexto, o presente estudo teve como objetivo analisar, por meio de uma abordagem bibliométrica, a evolução da produção científica global sobre a bioacumulação desses contaminantes em *Acanthocybium solandri* e *Thunnus albacares*, no período de 1973 a 2026. Os dados foram obtidos a partir das bases Scopus e Web of Science, resultando em um conjunto final de 112 artigos científicos. As análises foram realizadas utilizando o pacote Bibliometrix no ambiente R, permitindo avaliar indicadores de produtividade, colaboração científica e estrutura temática. Os resultados evidenciaram um crescimento não linear da produção científica, com intensificação a partir da década de 2010. A literatura concentrou-se em periódicos de alto impacto na área ambiental, com destaque para Science of the Total Environment e Marine Pollution Bulletin. A produção científica apresentou distribuição concentrada em países e instituições de nações desenvolvidas, com aumento progressivo da participação de países emergentes. A análise de palavras-chave indicou a predominância de termos como mercury, bioaccumulation e heavy metals, refletindo os riscos associados ao consumo de pescado. Destaca-se a expressiva assimetria na representação das espécies, com predominância de estudos sobre *T. albacares* e sub-representação de *A. solandri*.

Palavras-chave: contaminação ambiental; ecotoxicologia marinha; peixes pelágicos; segurança alimentar; yellowfin tuna; wahoo.

ABSTRACT

Metal and metalloid contamination in high trophic-level marine fish has become an increasing concern at the interface between ecotoxicology and public health. In this context, the present study aimed to analyze, through a bibliometric approach, the evolution of global scientific production on the bioaccumulation of these contaminants in *Acanthocybium solandri* and *Thunnus albacares* from 1973 to 2026. Data were retrieved from the Scopus and Web of Science databases, resulting in a final dataset of 112 scientific articles. Analyses were performed using the Bibliometrix package in the R environment, allowing the evaluation of productivity indicators, scientific collaboration, and thematic structure. The results revealed a non-linear growth in scientific production, with a marked increase from the 2010s onward. The literature was concentrated in high-impact environmental journals, particularly Science of the Total Environment and Marine Pollution Bulletin. Scientific production showed a geographically concentrated distribution in developed countries and institutions, although an increasing participation of emerging countries was observed over time. Keyword analysis indicated the predominance of terms such as mercury, bioaccumulation, and heavy metals, reflecting concerns related to seafood consumption and human exposure risks. A pronounced asymmetry in species representation was also identified, with a predominance of studies focused on *T. albacares* and a marked underrepresentation of *A. solandri*.

Keywords: marine ecotoxicology; food safety; pelagic fish; environmental contamination; wahoo, yellowfin tuna.

1. INTRODUÇÃO

A contaminação por metais e metaloides em ecossistemas marinhos tem sido reconhecida como um dos principais desafios contemporâneos da ecotoxicologia. Metais são elementos químicos caracterizados por elevada densidade e capacidade de formar cátions em solução, enquanto metaloides apresentam propriedades intermediárias entre metais e não-metais, o que condiciona seu comportamento ambiental e seus mecanismos de toxicidade (Tchounwou et al., 2012). Em função da persistência ambiental desses elementos, de sua elevada estabilidade química e da capacidade de acumulação em organismos aquáticos (Ali et al., 2019), sua presença nos oceanos representa uma ameaça crescente à integridade dos ecossistemas. Diferentemente de contaminantes orgânicos, metais e metaloides não sofrem degradação, sendo continuamente redistribuídos entre água, sedimentos e biota, o que favorece sua incorporação em diferentes níveis tróficos e amplia seu potencial de transferência ao longo das cadeias alimentares (Gao et al., 2021; Ray e Vashishth, 2024).

Nesse contexto, a bioacumulação em peixes marinhos de interesse comercial representa uma interface entre a contaminação ambiental e a saúde pública, ilustrando os princípios da abordagem One Health, segundo a qual a saúde humana, animal e dos ecossistemas são interdependentes (Whitmee et al., 2015). O consumo de pescado constitui uma das principais vias de exposição humana a elementos potencialmente tóxicos (Castro-González e Méndez-Armenta, 2008; Rahman et al., 2026), e a magnitude desse processo depende de múltiplos fatores biológicos e ecológicos, incluindo o nível trófico, a longevidade, o comportamento migratório e a taxa metabólica das espécies, além das características físico-químicas dos elementos envolvidos (Liu et al., 2026; Wang et al., 2026). Como consequência, espécies predadoras de alto nível trófico tendem a apresentar concentrações mais elevadas de metais em seus tecidos, refletindo a integração de processos de bioacumulação e biomagnificação ao longo do tempo (Gao et al., 2021; Bi et al., 2026).

Tal integração temporal e espacial torna os metais detectados em tecidos musculares e órgãos de grandes peixes pelágicos informativos não apenas sobre a qualidade ambiental local, mas sobre a saúde dos oceanos em escala regional e global. Adicionalmente, a relevância econômica e alimentar dessas espécies — cujo consumo per capita cresce consistentemente nos mercados mundiais (FAO, 2024) — amplia a

dimensão do problema, vinculando as concentrações de metais em pescado à exposição humana e, conseqüentemente, à saúde pública.

Entre os peixes pelágicos de grande porte, *Thunnus albacares* (Bonnaterre, 1788) — o atum-amarelo — e *Acanthocybium solandri* (Cuvier, 1832) — a cavala-da-índia — destacam-se por sua ampla distribuição nas zonas tropical e subtropical dos oceanos Atlântico, Índico e Pacífico, por sua relevância ecológica como predadores de topo e por sua importância econômica e alimentar (Zischke, 2012; Pecoraro et al., 2017). Ambas as espécies são altamente migratórias, alimentando-se predominantemente de peixes, cefalópodes e crustáceos, o que as expõe de forma contínua a contaminantes acumulados ao longo da cadeia alimentar (Júnior et al., 2003; Baque-Menoscal et al., 2012; Martins et al., 2024). A posição trófica aliada à capacidade de percorrer extensas áreas oceânicas, favorece a integração de diferentes fontes de contaminação, tornando a avaliação da bioacumulação de metais e metalóides nessas espécies relevante sob as perspectivas ecotoxicológica e de segurança alimentar (Lozano-Bilbao et al., 2023).

Nesse contexto, ambas as espécies apresentam elevada relevância comercial no cenário global. A espécie *T. albacares* destaca-se como uma das principais espécies de atum, constituindo um dos principais recursos das pescarias industriais, com capturas anuais que ultrapassam 1,5 milhão de toneladas, equivalendo a aproximadamente 25–30% do total das capturas mundiais de atuns (FAO, 2024). *A. solandri*, por sua vez, também possui elevado valor comercial, sendo amplamente explorada em pescarias em regiões tropicais e subtropicais (Theisen e Baldwin, 2012; Gao et al., 2020). Em função dessa importância, a musculatura dessas espécies tem sido investigada em estudos de monitoramento ambiental e segurança alimentar, dada sua importância como commodity global e a ampla aceitação do seu consumo em cru, como sushi e sashimi, modalidade que elimina qualquer eventual redução de concentração por processamento térmico (Burger et al., 2014). Estudos conduzidos em diferentes regiões oceânicas têm documentado a ocorrência de metais e metalóides, incluindo arsênio, cádmio, chumbo, cobre, mercúrio, zinco e selênio, em concentrações variáveis, refletindo tanto diferenças ambientais quanto aspectos fisiológicos e ecológicos da espécie (Kojadinovic et al., 2007; Norhazirah et al., 2020).

A produção científica sobre bioacumulação de metais e metalóides em peixes marinhos de grande porte encontra-se dispersa por um conjunto diversificado de periódicos especializados, abarcando perspectivas ecotoxicológicas, analíticas e de segurança dos alimentos (Franco-Fuentes et al., 2023; Oros, 2025; Spanu et al., 2026).

Diante do volume crescente de publicações na área e da fragmentação temática e geográfica do conhecimento acumulado, abordagens metodológicas que permitam a síntese quantitativa e sistemática dessa literatura tornam-se imprescindíveis para identificar tendências, lacunas e prioridades de investigação.

A bibliometria — definida como a aplicação de métodos estatísticos e matemáticos à análise da produção científica — constitui uma dessas abordagens, permitindo avaliar o desempenho de autores, instituições, países e periódicos, mapear redes de colaboração, identificar a estrutura temática de um campo e rastrear a evolução do conhecimento ao longo do tempo (Aria e Cuccurullo, 2017; Donthu et al., 2021). A utilização de bases de dados de ampla cobertura internacional — como a Scopus e a Web of Science — garante representatividade e reprodutibilidade às análises, aumentando a validade dos padrões identificados em relação à produção científica global (Mongeon e Paul-Hus, 2016).

Não obstante o crescimento das análises bibliométricas aplicadas à ecotoxicologia aquática, ainda não há, até o presente momento, um mapeamento sistemático e quantitativo da produção científica global voltada à bioacumulação de metais e metaloides especificamente em *A. solandri* e *T. albacares*. Diante dessa lacuna, o presente estudo teve como objetivo realizar uma análise bibliométrica abrangente da literatura científica sobre essas espécies, visando caracterizar a evolução temporal das publicações, identificar os periódicos mais influentes, os principais autores e instituições de pesquisa, bem como os países com maior contribuição científica e a estrutura temática do campo, a partir de dados extraídos de bases internacionais de referência e analisados por meio de ferramentas de mapeamento científico.

2. METODOLOGIA

A coleta de dados foi realizada nas bases de dados Scopus e Web of Science, selecionadas em função de sua ampla cobertura de periódicos científicos e qualidade dos registros indexados (Mongeon e Paul-Hus, 2016). A estratégia de busca foi definida com o uso de operadores booleanos, combinando termos relacionados às espécies de interesse e aos principais descritores de contaminação ambiental. Foram utilizados os seguintes termos: ("Acanthocybium solandri" OR "wahoo" OR "Thunnus albacares" OR "yellowfin tuna") AND ("heavy metals" OR "trace metals" OR "risk assessment" OR "mercury" OR "bioaccumulation" OR "biomagnification"). Embora a estratégia de busca tenha incluído descritores amplos e parcialmente sobrepostos (como “heavy metals”, “trace metals”) esses termos foram intencionalmente mantidos com o objetivo de maximizar a sensibilidade da recuperação bibliográfica e evitar a exclusão de estudos relevantes indexados sob terminologias distintas.

Não foi estabelecido recorte temporal, sendo considerados todos os registros disponíveis até o ano de 2026. A busca foi aplicada aos campos de título, resumo e palavras-chave dos documentos. Em seguida, foi realizada a verificação da aderência dos documentos ao tema da pesquisa, mantendo-se apenas aqueles diretamente relacionados às espécies e à temática de contaminação por metais e metaloides. Foram incluídos exclusivamente artigos científicos revisados por pares, sendo excluídos outros tipos de documentos, como revisões, editoriais, capítulos de livros e trabalhos publicados em anais de eventos.

Os resultados obtidos nas duas bases foram exportados em formato BibTeX e, depois da remoção de registros duplicados, foram consolidados em um único conjunto de dados. O processamento dos dados foi realizado no ambiente estatístico R (R Core Team, 2023), utilizando o pacote Bibliometrix e a interface do Biblioshiny (Aria e Cuccurullo, 2017).

3. RESULTADOS E DISCUSSÃO

A análise bibliométrica da produção científica sobre contaminação por metais pesados em *Acanthocybium solandri* e *Thunnus albacares* revelou um conjunto de 112 artigos publicados entre 1973 e 2026, evidenciando a evolução gradual do interesse científico sobre o tema ao longo dos últimos 53 anos. De modo geral, observa-se a consolidação do campo a partir dos anos mais recentes, acompanhando a expansão global da produção científica e da indexação em bases de dados internacionais, das preocupações relacionadas à segurança alimentar e à exposição humana a contaminantes ambientais.

Para uma visão geral da estrutura da produção científica analisada, a Figura 1 reúne os principais indicadores bibliométricos ao longo do período estudado, incluindo aspectos relacionados ao crescimento das publicações, à interação entre pesquisadores e ao impacto dos estudos. A análise conjunta desses parâmetros permite compreender a evolução e a dinâmica de desenvolvimento do campo e das espécies ao longo do tempo.



Figura 1. Resumo dos principais indicadores bibliométricos (1973–2026) relacionados à pesquisa sobre contaminação por metais e metalóides em *Acanthocybium solandri* e *Thunnus albacares*. As métricas incluem o total de publicações, fontes, tendências de autoria, taxa de colaboração internacional, taxa de crescimento anual, impacto de citações e diversidade de palavras-chave temáticas.

3.1 TENDÊNCIA ANUAL DAS PUBLICAÇÕES

A produção científica sobre contaminação por metais pesados em *A. solandri* e *T. albacares* apresenta um padrão de crescimento não linear, caracterizado por uma fase inicial de baixa produtividade, seguida por uma intensificação progressiva nas últimas décadas (Figura 2). Embora os primeiros registros remontem à década de 1970, o campo permaneceu pouco explorado por um longo período, o que pode refletir tanto as

limitações das técnicas analíticas disponíveis à época quanto a menor ênfase, naquele contexto, nos efeitos ecotoxicológicos e nas implicações para a saúde humana associadas a esses contaminantes em espécies pelágicas específicas.

A inflexão no padrão de crescimento torna-se mais evidente a partir da década de 2010, quando se observa maior regularidade e aumento na frequência das publicações. Esse comportamento sugere uma consolidação recente do tema, possivelmente impulsionada pelo avanço das técnicas analíticas, pela ampliação do monitoramento ambiental e pelo reconhecimento crescente dos riscos associados à bioacumulação de metais em espécies de alto nível trófico.

A partir de 2019, a produção científica apresenta um aumento mais expressivo, indicando uma fase de intensificação da atividade de pesquisa. Esse padrão pode estar relacionado ao fortalecimento de agendas científicas voltadas à segurança alimentar e à avaliação de risco, especialmente no contexto de espécies amplamente consumidas e de elevada importância econômica. Ainda que oscilações anuais sejam observadas, a tendência acumulada evidencia um crescimento contínuo da literatura, culminando em 112 publicações até 2026.

A taxa de crescimento anual de 3,51% indica aumento gradual da produção científica ao longo do período analisado. No entanto, considerando o recorte específico adotado, esse padrão sugere que a literatura sobre bioacumulação de metais e metaloides em *A. solandri* e *T. albacares* ainda se encontra em desenvolvimento, com limitações na integração entre estudos de bioacumulação, biomagnificação e avaliação de risco à saúde humana.

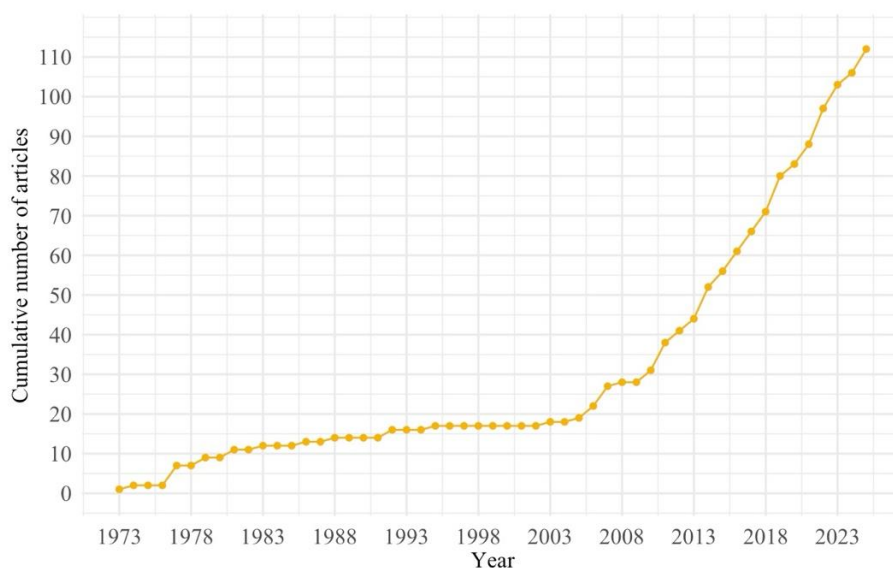


Figura 2. Evolução acumulada das publicações científicas sobre contaminação por metais e metaloides em *Acanthocybium solandri* e *Thunnus albacares* no período de 1973 a 2026.

3.2 PRINCIPAIS PERIÓDICOS DE PUBLICAÇÕES

A produção científica analisada concentra-se em um conjunto restrito de periódicos de elevado impacto, com destaque para *Science of the Total Environment* e *Marine Pollution Bulletin*, que figuram como os principais veículos de disseminação do conhecimento na área (Figura 3). Esse padrão sugere a concentração da produção científica em periódicos com forte tradição na publicação de estudos voltados à contaminação ambiental e ecotoxicologia marinha.

Em posição intermediária, a presença do *Food Additives & Contaminants Part B-Surveillance* nesse grupo sinaliza que a dimensão da vigilância alimentar constitui uma vertente substantiva do conjunto analisado, complementar às abordagens puramente ecológicas (Nguyen et al., 2026). O *Biological Trace Element Research*, por sua vez, reflete a interface entre toxicologia e fisiologia, indicando que parte dos estudos aborda também os mecanismos de bioconcentração e os limiares de toxicidade em organismos-alvo (Habib et al., 2024).

Por fim, *Foods*, *Environmental Toxicology and Chemistry*, *Environmental Science & Technology* e *Chemosphere* contribuirão com três artigos cada, compondo o estrato de menor frequência. A presença desses quatro periódicos, embora em menor número de artigos, é expressiva porque reflete a amplitude disciplinar da literatura sobre metais pesados em peixes: do monitoramento e avaliação de risco via consumo alimentar (Lozano-Bilbao et al., 2023) à ecotoxicologia, com ênfase na transferência trófica e especiação de contaminantes em organismos aquáticos (Morrison et al., 2023), passando pela toxicologia fisiológica e os efeitos sistêmicos da exposição crônica a metais em tecidos e órgãos de peixes (Shahjahan et al., 2022).

De modo geral, o perfil dos periódicos identificados aponta para uma literatura multidisciplinar, situada na intersecção entre ecologia química, toxicologia ambiental e segurança dos alimentos. A ausência de periódicos clínicos ou biomédicos entre os mais frequentes sugere, ademais, que a perspectiva predominante nos estudos é a do monitoramento ambiental e da avaliação de exposição alimentar, e não a da resposta toxicológica em populações humanas clinicamente acompanhadas.

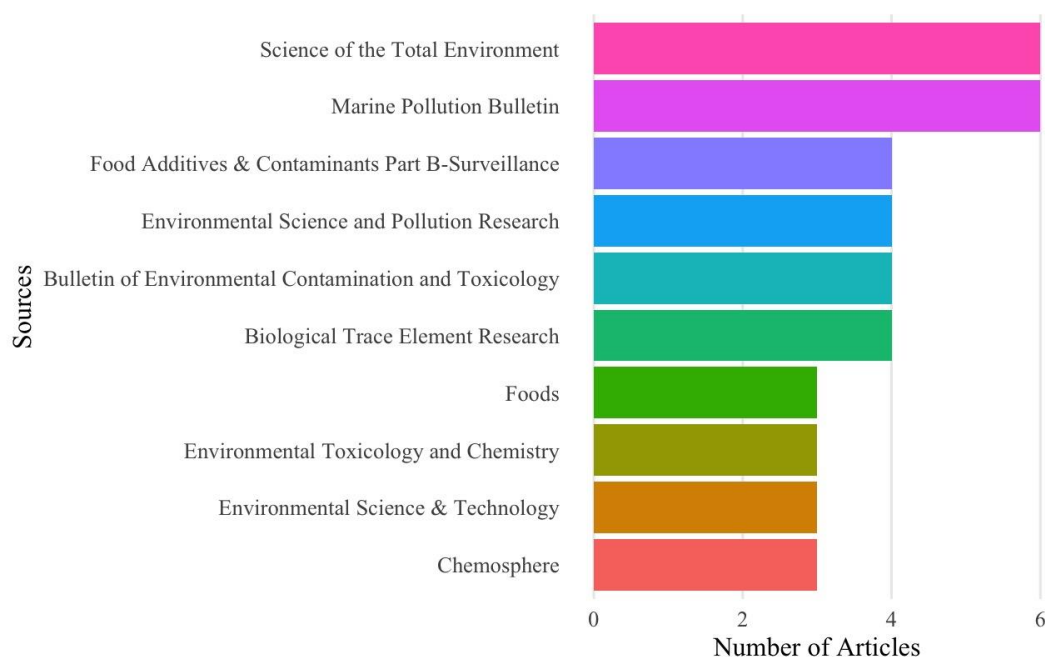


Figura 3. Principais periódicos que publicam sobre contaminação por metais e metaloides em *Acanthocybium solandri* e *Thunnus albacares* no período de 1973 a 2026.

3.3 PRINCIPAIS AFILIAÇÕES EM PESQUISA

A análise das afiliações institucionais revela distribuição múltipla da produção científica, com a Universidad de La Laguna liderando o conjunto com dez artigos, seguida pela Università degli Studi di Messina e pela Islamic Azad University ($n = 8$ cada). Esse padrão sugere a existência de centros acadêmicos com maior consolidação na temática, possivelmente associados à continuidade de linhas de pesquisa específicas e à formação de grupos especializados — fatores amplamente reconhecidos como determinantes da produtividade científica (Wuchty et al., 2007).

Adicionalmente, observa-se a presença simultânea de instituições de diferentes contextos geográficos e níveis de desenvolvimento científico, o que indica que a produção na área não está restrita a um único eixo institucional. Esse aspecto reforça a ideia de que o campo apresenta múltiplos núcleos ativos de pesquisa, ainda que com níveis distintos de contribuição. A distribuição relativamente gradual entre as instituições, sem domínio absoluto de uma única afiliação, pode refletir tanto o crescimento geral da produção científica quanto a expansão do tema, nos quais diferentes grupos institucionais contribuem de maneira complementar para o avanço do conhecimento (Ellegaard & Wallin, 2015).

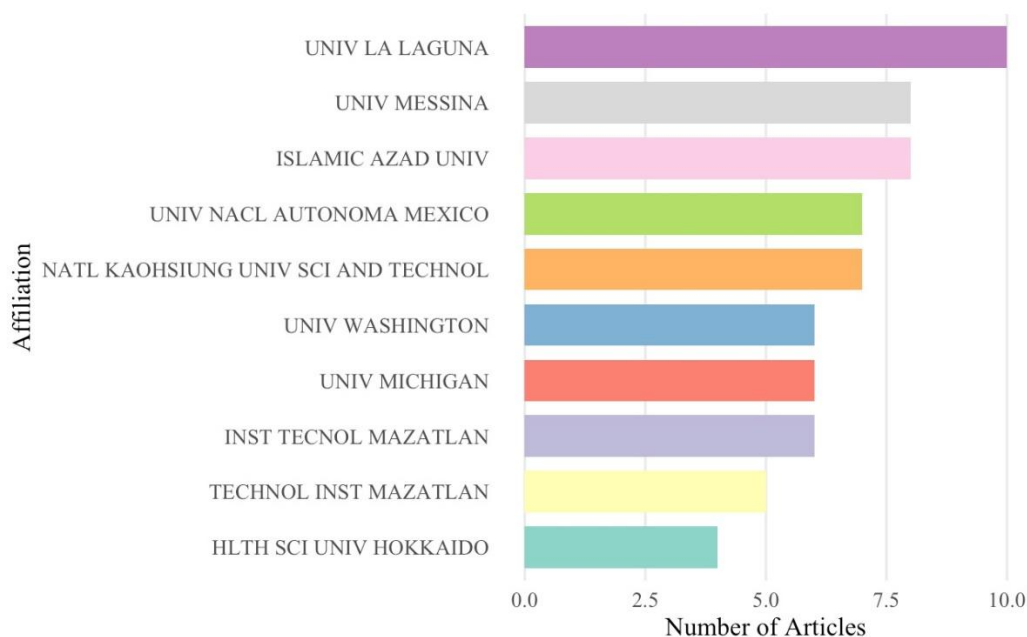


Figura 4. Principais afiliações em pesquisas sobre contaminação por metais e metalóides em *Acanthocybium solandri* e *Thunnus albacares* no período de 1973 a 2026. Abreviações: Univ La Laguna = University of La Laguna; Islamic Azad Univ = Islamic Azad University; Univ Messina = University of Messina; Natl Kaohsiung Univ Sci and Technol = National Kaohsiung University of Science and Technology; Univ NACL Autonoma Mexico = Universidad Nacional Autónoma de México; Inst Tecnol Mazatlan = Instituto Tecnológico de Mazatlán; Univ Michigan = University of Michigan; Univ Washington = University of Washington; Technol Inst Mazatlan = Technological Institute of Mazatlán; Hlth Sci Univ Hokkaido = Health Sciences University of Hokkaido.

3.4 PAÍSES MAIS RELEVANTES

A análise da produtividade por país, estratificada entre publicações de país único (Single Country Publications — SCP) e publicações multinacionais (Multiple Country Publications — MCP), demonstrou distribuição assimétrica com predomínio de poucos países (Figura 6). Os Estados Unidos lideraram o conjunto com 15 documentos e a maior proporção absoluta de MCP, seguidos pelo Japão ($n = 14$) e pela Espanha ($n = 10$), ambos com predominância de SCP. México ($n = 9$), Brasil ($n = 5$), Índia ($n = 5$) e Irã ($n = 5$) compuseram o grupo intermediário, enquanto os demais países contribuíram com quatro ou menos documentos cada.

A predominância de SCP na maioria dos países sugere que a produção na área ainda é conduzida majoritariamente em âmbito nacional. No entanto, a elevada proporção de MCP dos Estados Unidos indica que esse país atua não apenas como produtor independente, mas como nó central nas redes de colaboração internacional, papel consistente com sua posição estrutural na ciência global (Adams, 2013). A presença de países de renda média — Brasil, México, Índia e Irã — entre os mais produtivos reflete a

expansão geográfica da capacidade científica documentada nas últimas décadas, ainda que com baixa participação em colaborações multinacionais, o que pode indicar limitações no grau de inserção dessas instituições nas redes internacionais de pesquisa (Chinchilla-Rodríguez et al., 2018).

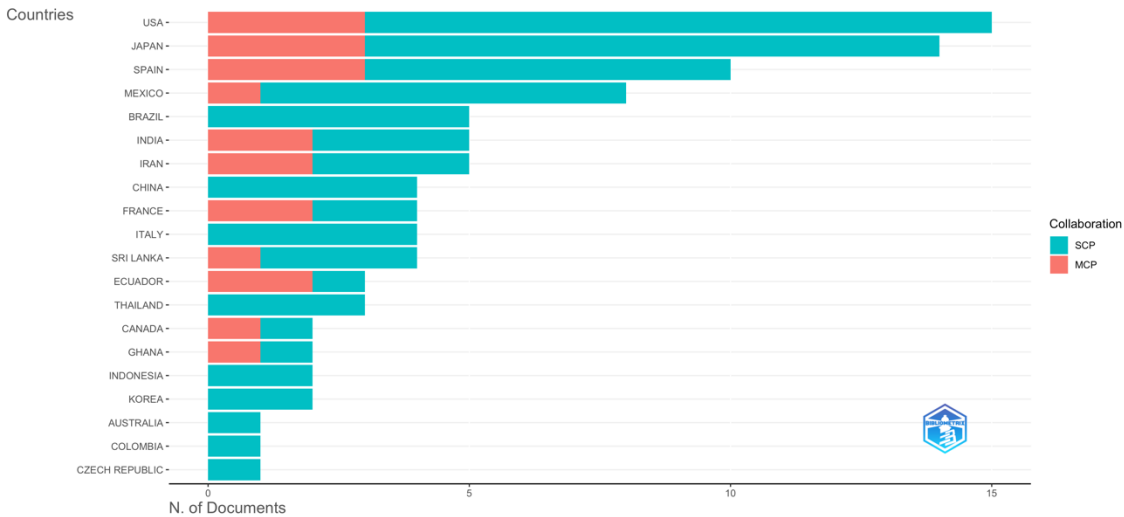


Figura 6. Contribuições globais para a pesquisa sobre contaminação por metais e metaloides em *Acanthocybium solandri* e *Thunnus albacares*, analisadas por país do autor correspondente, a partir de dados coletados do Scopus e Web of Science (1973 – 2026).

3.5 CONTRIBUIÇÕES DOS AUTORES

A produção científica sobre contaminação por metais pesados em *A. solandri* e *T. albacares* apresenta baixa concentração de produtividade autoral, sem evidência de dominância por um grupo restrito de pesquisadores. Conforme evidenciado na Tabela 1, Ruelas-Inzunza J destaca-se como o autor mais produtivo (NP = 6; h-index = 5), enquanto Bustamante P apresenta o maior número de citações totais (TC = 456), indicando maior impacto médio por publicação. Adicionalmente, valores elevados de m-index, como observado para Hardisson A (0,667), sugerem crescimento recente de impacto.

Tabela 1. Os 10 principais autores que contribuíram para a pesquisa sobre contaminação por metais e metaloides em *Acanthocybium solandri* e *Thunnus albacares*.

Autor	H_Inde x	G_Inde x	M_Index	Citações Totais	Número de Publicações
RUELAS-INZUNZA J	5	6	0,313	107	6
BUSTAMANTE P	4	4	0,190	456	4
HARDISSON A	4	5	0,667	66	5
ANDRADE-VERA S	3	3	0,500	52	3
ANGELES G M	3	3	0,273	95	3

ESSINGTON T	3	3	0,188	62	3
FERRISS B	3	3	0,188	62	3
FRANCO-FUENTES E	3	3	0,500	52	3
GUTIERREZ A	3	3	0,500	56	3
HOSSEINI S	3	3	0,214	115	3

A dimensão temporal da produção autoral (Figura 5) permite qualificar esses padrões ao evidenciar diferenças na regularidade das contribuições. Observa-se que parte dos autores apresenta produção distribuída ao longo de múltiplos anos, enquanto outros concentram suas publicações em intervalos temporais mais restritos. Há ainda casos de produção esporádica, com registros isolados ao longo do período analisado. Esses resultados indicam que as diferenças entre os autores não se restringem ao volume e impacto das publicações, mas também à forma como a produção científica se organiza temporalmente.

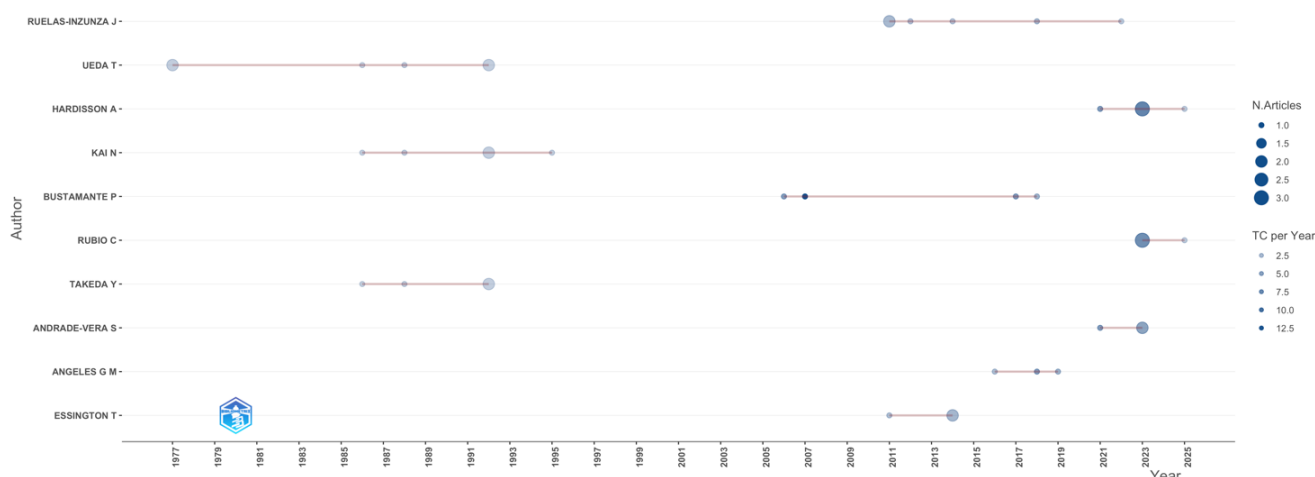


Figura 5. Produção científica ao longo do tempo sobre contaminação por metais e metaloides em *Acanthocybium solandri* e *Thunnus albacares* no período de 1973 a 2026.

3.6 ANÁLISE DE PALAVRAS-CHAVE

A análise das palavras-chave demonstra a predominância de termos relacionados à contaminação por metais e seus efeitos em organismos marinhos, com destaque para mercury, bioaccumulation, selenium, methylmercury, e heavy-metals que configuram os principais eixos temáticos da literatura (Figura 7). A elevada frequência desses termos indica forte concentração de estudos voltados à dinâmica de bioacumulação e aos potenciais riscos associados ao consumo de peixes, especialmente no contexto de metais de alta relevância toxicológica, como o mercúrio. Cabe ressaltar que a adoção exclusiva de descritores em inglês pode introduzir um viés linguístico nos resultados, favorecendo

a recuperação de estudos indexados em bases internacionais de língua inglesa em detrimento de produções publicadas em outros idiomas ou regionais de menor abrangência global.

O termo mercury destacou-se como o de maior frequência no conjunto, o que é consistente com o reconhecimento global do mercúrio como o contaminante metálico de maior preocupação em produtos pesqueiros de origem marinha. Isso se deve, particularmente, à sua capacidade neurotóxica na conversão para a forma orgânica metilmercúrio (MeHg), e de sua marcada tendência à biomagnificação ao longo da cadeia trófica (Karagas et al., 2012; Cossa et al., 2022). A co-ocorrência de elevada frequência de methylmercury e selenium na mesma nuvem é particularmente relevante do ponto de vista toxicológico: o selênio é amplamente reconhecido como modulador da toxicidade do mercúrio em tecidos de peixes e humanos, por meio da formação de complexos seleneto-mercúrio que reduzem a biodisponibilidade da forma tóxica (Burger e Gochfeld, 2012; Ralston et al., 2016).

O par bioaccumulation e heavy metals sugere que parcela expressiva dos estudos aborda a dinâmica de acúmulo tecidual de contaminantes nas duas espécies, evidenciando orientação ecotoxicológica que transcende a mera detecção ambiental, o que confere ao conjunto uma orientação ecotoxicológica e de saúde pública mais do que puramente analítica. Em posição de destaque encontram-se também cádmio e chumbo, dois dos metais pesados classificados como prioritários pela Autoridade Europeia para a Segurança dos Alimentos (EFSA) e pelo Comitê Conjunto FAO/OMS de Especialistas em Aditivos Alimentares (JECFA), dada a evidência acumulada de sua nefrotoxicidade e neurotoxicidade em mamíferos (EFSA, 2010; EFSA, 2011; WHO, 2011; Satarug et al., 2020).

No que diz respeito às espécies investigadas, a nuvem de palavras-chave revela uma assimetria expressiva entre as duas espécies que delimitaram o tema da presente revisão. *Thunnus albacares* apresentou representação proeminente no conjunto, figurando sob os termos yellowfin tuna e *Thunnus albacares*, o que reflete o volume consolidado de investigações sobre bioconcentração de metais pesados nessa espécie, amplamente estudada em razão de ser uma das espécies comerciais de maior volume mundial, alvo de frotas industriais e objeto de monitoramento, o que sustenta uma demanda científica contínua (Ormaza-González et al., 2020; Bae et al., 2023; Lehel et al., 2023). *A. solandri*, por outro lado, esteve virtualmente ausente da estrutura de palavras-chave dos artigos recuperados. Por se tratar de uma espécie capturada predominantemente

como fauna acompanhante incidental em pescarias voltadas ao atum e ao espadarte, com volumes de captura muito inferiores comparadas ao atum e ausência de avaliações de estoque formais na maior parte das regiões, sua presença na literatura científica é estruturalmente limitada (Zischke, 2012; Kindong et al., 2022). Essa lacuna não deve ser interpretada como ausência de risco toxicológico nessa espécie, mas como reflexo de sua sub-representação nos programas internacionais de monitoramento de contaminantes em pescado.

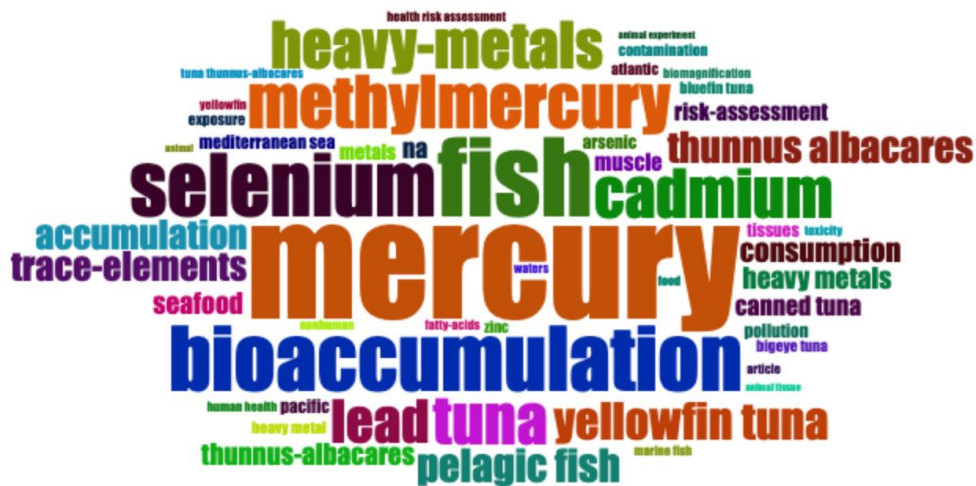


Figura 7. Nuvem de palavras representando a distribuição de frequência das palavras-chave. O tamanho de cada termo é proporcional à sua ocorrência no conjunto de dados.

4. CONSIDERAÇÕES FINAIS

A produção científica sobre metais e metaloides em *Acanthocybium solandri* e *Thunnus albacares* apresentou crescimento gradual ao longo do período analisado (1973–2026), com intensificação mais evidente nas últimas décadas, refletindo a consolidação recente do tema no âmbito da ecotoxicologia marinha e da segurança alimentar.

A literatura concentra-se em um conjunto restrito de periódicos de elevado impacto, predominantemente vinculados às áreas de ciência ambiental, ecotoxicologia e segurança dos alimentos, evidenciando o caráter multidisciplinar do campo. Em termos estruturais, a distribuição das publicações entre instituições e países demonstrou a atuação de múltiplos núcleos de pesquisa, sem predominância absoluta, com participação heterogênea e contribuição relevante de diferentes contextos geográficos.

A análise da produtividade autoral indicou baixa concentração de publicações por pesquisador, sem domínio de grupos específicos, e com variações na regularidade temporal das contribuições. No âmbito geográfico, observou-se predominância de publicações conduzidas em escala nacional, embora com participação expressiva de alguns países em colaborações internacionais.

Do ponto de vista temático, a literatura recuperada concentra-se na bioacumulação de mercúrio e metilmercúrio, na interação com o selênio e na avaliação de risco ao consumo humano — diretamente vinculada à neurotoxicidade do MeHg e à sua tendência à biomagnificação em predadores de topo. A análise evidenciou ainda uma assimetria expressiva entre as espécies investigadas, onde *T. albacares* apresentou representação proeminente, ao passo que *A. solandri* esteve virtualmente ausente da estrutura de palavras-chave, refletindo sua sub-representação nos programas internacionais de monitoramento de contaminantes em pescado, mas que não significa ausência de risco toxicológico.

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Capítulo 2: Bioaccumulation of metals and metalloids in Yellowfin tuna and Wahoo (Scombridae) in the Saint Peter and Saint Paul Archipelago, Brazil

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ABSTRACT

The investigation of metal and metalloid contamination in marine ecosystems has gained increasing relevance in ecotoxicology due to their potential for bioaccumulation, even in remote areas such as the Saint Peter and Saint Paul Archipelago (SPSPA). This study assessed the concentrations of 14 elements (Ag, Al, As, Ba, Cd, Cr, Cu, Fe, Li, Mn, Hg, Pb, Se, and Zn) in the muscle tissue of *Acanthocybium solandri* (wahoo) and *Thunnus albacares* (yellowfin tuna), as well as their relationship with fish length, compliance with legal limits, and associated human health risks. Essential metals predominated in both species, with Zn and Fe exhibiting the highest mean concentrations, whereas Al was the most prominent among non-essential elements. Statistically significant interspecific differences were observed for Cd, Cu, Fe, Se, and Zn ($p < 0.05$), while significant negative correlations were identified for Se in *A. solandri* and for Al and Fe in *T. albacares*. In relation to Maximum Tolerance Limits, *A. solandri* exceeded the threshold for Pb and showed localized exceedance for Cd, whilst *T. albacares* complied with all regulated limits. Risk assessment revealed that Cr, Se, Cd, Pb, and Zn were the principal contributors to non-carcinogenic risk, with THQ and TTHQ values exceeding safety thresholds across all consumption scenarios, while carcinogenic risk associated with As surpassed acceptable levels only at maximum concentrations. These findings demonstrate that, despite apparent regulatory compliance, both species pose potential risks to human health due to cumulative exposure, highlighting the need to strengthen environmental monitoring and regulatory frameworks in the SPSPA.

Keywords: food safety, inorganic contaminants, marine fish, risk assessment.

1 INTRODUCTION

Fish consumption represents one of the primary sources of animal protein in the human diet (FAO, 2024). In addition to being highly bioavailable and easily digestible, fish constitute a source of a broad spectrum of essential nutrients, including omega-3 fatty acids, vitamins, and minerals (ABERA and ADIMAS, 2024). These nutrients play a critical role in preventing nutritional deficiencies and promoting human health. This nutritional significance underscores the relevance of the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger and Sustainable Agriculture) and SDG 3 (Good Health and Well-Being), established by the United Nations in 2015 with targets set for 2030. However, the potential of fish to bioaccumulate contaminants, notably metals and metalloids in their muscle tissue, poses a risk to food safety. These elements originate from water and sediments and can accumulate in organisms via bioaccumulation and biomagnification, processes by which potentially toxic elements accumulate within organisms over time and throughout the trophic chain, respectively (MILLER et al., 2020).

Metals and metalloids, present at varying concentrations in environmental compartments, serve diverse roles within ecosystems and are classified as essential or non-essential. Essential metals, such as zinc (Zn), copper (Cu), and iron (Fe), are critical elements for organismal function in balanced quantities, involved in key biological processes including oxygen transport and enzymatic regulation (CHANDRAPALAN and KWONG, 2021; SUN et al., 2023). Non-essential metals and metalloids, such as arsenic (As), lead (Pb), and cadmium (Cd), are not required for physiological processes and can be toxic at concentrations lower than those of essential elements (DALTO et al., 2023; DEMIRCAN et al., 2024). Furthermore, these elements have a greater capacity to bioaccumulate along the food chain compared to essential metals (GAO et al., 2022).

The analysis of the occurrence and concentration of metals and metalloids in biotic and abiotic compartments is a valuable approach for monitoring environmental contamination, enabling the detection and quantification of element levels that may pose risks to ecosystems and human health (TCHOUNWOU et al., 2012). It also serves as an environmental indicator of anthropogenic pressures. Anthropogenic processes, including industrial pollution and the exploitation of natural resources such as petroleum (SPILSBURY et al., 2022), have accelerated the contamination of marine ecosystems by

increasing the natural concentrations of these elements, thereby rendering their levels in seafood increasingly concerning (NICKLISCH et al., 2021; TIKADAR et al., 2024).

Bioaccumulation is influenced by factors such as the size, age, diet, and habitat of organisms, and occurs when organisms absorb metals or metalloids at a rate higher than they can eliminate them. This process can contribute to biomagnification along trophic chains, where the concentration of certain elements increases at successive trophic levels (CONARD et al., 2021). Larger adult fish are generally the most commercially traded and tend to have higher concentrations of these elements, as they are exposed for longer periods and consume prey that have accumulated the elements along the lower levels of the food chain (LACERDA et al., 2017). Certain contaminants can persist in tissues for prolonged periods, causing toxic effects or even mortality, unless the organism can eliminate them through detoxification or excretion processes (TASLIMA et al., 2022). This accumulation is particularly significant in large predators, such as the marine fish wahoo (*Acanthocybium solandri*) and yellowfin tuna (*Thunnus albacares*), whose high position in marine food chains intensifies the biomagnification of contaminants (SHIPLEY et al., 2019). Studies indicate that metals and metalloids preferentially accumulate in the liver, gonads, and muscle tissue (MARTINS et al., 2020; SHALINI et al., 2021; HASHIM et al., 2024), with muscle tissue being of greatest interest as it is the part consumed by humans. This poses a direct risk to human health, especially in communities with regular fish consumption.

International legislation from the World Health Organization (WHO) sets maximum allowable limits for metals and metalloids in food products to protect public health (WHO, 2023). In Brazil, the National Health Surveillance Agency (ANVISA) is responsible for controlling food contaminants through Maximum Tolerance Limits (MTL) for inorganic contaminants, as established in Normative Instruction No. 160, dated August 29, 2022. For metals and metalloids of major concern, The Maximum Tolerance Limits (MTL) established by ANVISA and WHO protocols in fish such as tuna and wahoo are: mercury 1.00 mg/kg, lead 0.30 mg/kg, arsenic 1.00 mg/kg, and cadmium 0.10 mg/kg. However, monitoring contaminant levels that exceed the legally established MTLs is not sufficient to assess the risk to human health, since it does not consider the amount of fish consumed or the frequency of exposure to these contaminants. Therefore, monitoring potentially toxic metals and metalloid levels in fish species is essential for assessing the risk of human exposure to these elements.

Thunnus albacares (yellowfin tuna) and *A. solandri* (wahoo) are pelagic species widely distributed across tropical and subtropical waters of the Atlantic, Pacific, and Indian Oceans, with significant ecological and economic importance (LOZANO-BILBAO et al., 2023). Due to their wide consumption, they have high commercial value and represent a substantial share of the commercial catches in various countries (TRIAY-PORTELLA et al., 2023; SOBRADILLO et al., 2024). Both species are highly migratory and occupy high levels in marine food chains, feeding mainly on small fish, crustaceans, and cephalopods (JÚNIOR et al., 2003; MARTINS et al., 2024). The feeding spectrum of *T. albacares* and *A. solandri* is highly susceptible to contamination by metals and metalloids, which promotes bioaccumulation and biomagnification processes (SHIPLEY et al., 2019). *Thunnus albacares* and *A. solandri* are common species in remote island formations such as the Saint Peter Saint Paul Archipelago (hereinafter SPSPA), a group of five islands far from the Brazilian coast but of significant ecological and socioeconomic importance due to their high biodiversity, their role as a reproductive refuge for various species (PINHEIRO et al., 2020), and the presence of important fishery stocks (VIANA et al., 2015). Studies conducted in the SPSPA revealed the presence of persistent organic pollutants (POPs) in marine organisms, indicating that even remote locations are not exempt from environmental contamination (DIAS et al., 2013; OLIVEIRA-FERREIRA et al., 2026). The concentrations of metals and metalloids in fishery resources from the Saint Peter Saint Paul Archipelago, however, have yet to be properly investigated.

The SPSPA holds strategic and scientific importance for Brazil, since it is one of the most remote areas under Brazilian jurisdiction, located approximately 1,100 km from the coast. It is a key hub of marine biodiversity and logistical support for oceanographic, fisheries, and conservation research, as well as contributing to national sovereignty over natural resources and to upholding the rights to explore the Exclusive Economic Zone (EEZ) (CONDE, 2019). Fishing in the archipelago has an average annual volume of approximately 100 tons, predominantly composed of *T. albacares* and *A. solandri*, which together represent the majority of the recorded landings over the 13 years of monitoring conducted by Viana et al. (2015). Furthermore, stomach content analyses reveal that both species use the archipelago as a feeding site, underscoring the ecological importance of the region (VASKE-JR. et al., 2005). The creation of the Environmental Protection Area (APA) of the SPSPA strengthens management and conservation strategies aimed at maintaining the ecological functioning of this ecosystem and ensuring

the safe use of fishery resources (ICMBIO, 2021). Few ecotoxicological studies address species from isolated oceanic areas like this archipelago.

In this context, owing to the great biodiversity of SPSPA and the predominance of yellowfin tuna and wahoo in the volume of fish caught (VIANA et al., 2015), the main objective of this study was to assess the concentrations of metals and metalloids—aluminum (Al), arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lithium (Li), manganese (Mn), mercury (Hg), lead (Pb), silver (Ag), selenium (Se), and zinc (Zn)—in these two species of marine fish widely consumed by humans. Additionally, we evaluated the relationship between the concentrations of the analyzed metals and metalloids and the size of the sampled individuals; we checked the compliance of the metal levels with current Brazilian and international legislation; and we assessed the potential human health risk associated with consuming these species by calculating the non-carcinogenic risk quotient (THQ), the total risk quotient (TTHQ), and the carcinogenic risk for arsenic (CR).

2 MATERIALS AND METHODS

2.1 STUDY AREA

The SPSPA is the most remote group of Brazilian islands in the Northern Hemisphere and also one of the smallest archipelagos in the world. The total emerged area is approximately 17,000 m², with a maximum elevation of 18 meters above sea level (CAMPOS et al., 2010). It is located about 1100 km off Brazil's northeastern coast (Figure 1) and 1.820 km from the Guinea-Bissau coast, in the African continent. The geological substrate is predominantly composed of ultramafic rocks, characterized by rugged relief, originating from a tectonic transition zone between the African and South American plates (CAMPOS et al., 2010). The archipelago lies within a region of strong interaction between ocean currents, particularly the South Equatorial Current and the Equatorial Current (TRAVASSOS et al., 1999). The region's climate is equatorial, characterized by high average annual temperatures and high relative humidity. The lack of freshwater sources on the islands limits terrestrial vegetation, but the region is an important stopover for migratory birds and supports a great diversity of marine organisms (NUNES et al., 2015; VIANA et al., 2015; CRUZ et al., 2022; OLIVEIRA-FERREIRA et al., 2026).

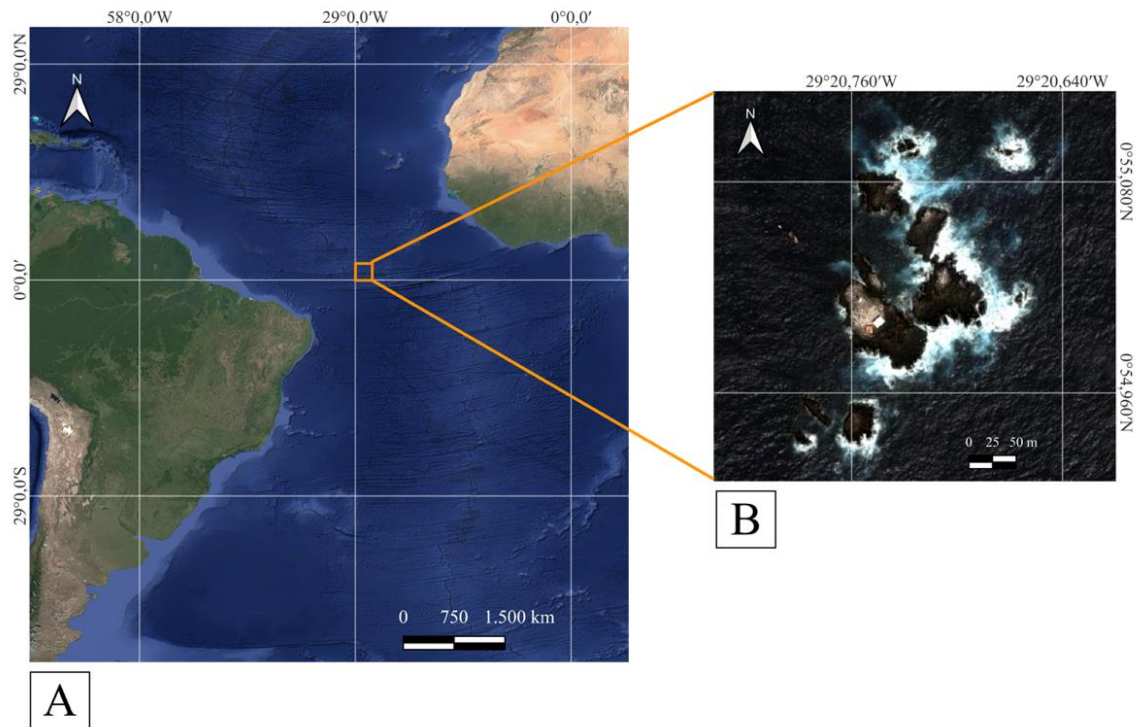


Figure 2. Location of the study area in the Atlantic Ocean (A) and the islands of the Saint Peter and Saint Paul Archipelago (B).

2.2 DATA COLLECTION

Twenty individuals of *A. solandri* and twenty of *T. albacares* were collected between December 2023 and January 2024. The fish were sampled from authorized longline catches by commercial fishers targeting wahoos and tunas (license number SISBIO/ICMBio: 74900-1). For each individual, a sample of epaxial muscle approximately 3×1 cm was taken from the lateral side of the body using a sterile blade, with masses ranging from 0.5201 to 1.6896 g (*A. solandri*) and from 0.5036 to 1.8005 g (*T. albacares*). The samples were stored in sterile Eppendorf-type microtubes and kept frozen at -8°C until the element determination step.

2.3 SAMPLE PREPARATION

Muscle samples were digested using acid on heating plates. Each sample was weighed and transferred to 50 mL Falcon tubes, to which 4 mL of concentrated nitric acid (HNO_3 65%) and 2 mL of concentrated hydrochloric acid (HCl 37%) were added. The samples were heated on the plate following these steps: (1) heating ramp to 180°C at $8^{\circ}\text{C}/\text{min}$; (2) hold for 10 minutes at 180°C ; (3) cooling down to 70°C . The digested solutions were accurately transferred to 50 mL polypropylene bottles and brought to a final volume of 50 mL with Milli-Q water. The same procedure was applied to prepare 6 blank samples (with addition of HNO_3 and HCl , but without biological material).

Metals (Ag, Al, Ba, Cd, Cr, Cu, Fe, Hg, Li, Mn, Pb and Zn) and metalloids (As and Se) were quantified by inductively coupled plasma optical emission spectrometry (ICP-OES, model ICPE 9820, Shimadzu), using argon (Messer, purity $> 99.99\%$) as the carrier and plasma gas. Samples were syringe-filtered through a PTFE membrane (Filtrilo, $0.45\ \mu\text{m} \times 25\ \text{mm}$). The equipment was calibrated using solutions with concentrations ranging from 10 to $200\ \mu\text{g}/\text{L}$, prepared from the multielement standard solution (Specsol, $10.00\ \text{mg}/\text{L}$) and the single-element standard solutions of As, Hg, and Se (Perkin Elmer $1000\ \text{mg}/\text{L}$, Supelco $1000\ \text{mg}/\text{L}$, and Fluka $1000\ \text{mg}/\text{L}$, respectively). The detection limit (detection limit) (Table 1) was calculated according to the recommendations of IUPAC and MAPA (2011) (detection limit $= 3 \cdot \sigma$), where σ is the standard deviation from 5 measurements of one of the blanks.

Table 2. Selected absorption wavelengths used in optical emission spectrometry and limits of detection (LOD) for the analyzed elements.

Element	Wavelength (nm)	LOD (mg/kg)
Ag	328.068	0.018

Al	167.081	1.00
As	193.759	0.007
Ba	233.527	0.012
Cd	214.438	0.018
Cr	205.552	0.030
Cu	324.754	0.062
Fe	238.204	0.126
Hg	184.95	0.005
Li	670.784	0.002
Mn	257.61	0.142
Pb	220.353	0.364
Se	203.985	0.006
Zn	202.548	0.89

2.4 DATA ANALYSIS

Means, standard deviations, and ranges of specific concentrations (expressed in µg/g wet weight [w.w.]) were calculated for the elements in each analyzed species. The data were tested for normality of value distribution using the Shapiro-Wilk test. Differences in element concentrations between species were assessed using the t-test for normally distributed data and the Mann-Whitney test for non-normal distributions. The relationship between metal concentrations and individual size was evaluated using Pearson correlation tests for normally distributed data and Spearman correlation tests for non-parametric data. The significance level was set at $p < 0.05$, and all analyses were conducted using R software (R Core Team 2024). The obtained values were also compared with the maximum recommended daily intake for the quantified elements—when available—for a 70 kg person, according to WHO (1992, 1997, 1998, 2011a) and EFSA (2010, 2014).

2.5 HUMAN HEALTH RISK ASSESSMENT

The non-carcinogenic risk associated with the consumption of fish contaminated with heavy metals was assessed by calculating the Target Hazard Quotient (THQ) for each metal individually, following the methodology proposed by the United States Environmental Protection Agency (USEPA, 2000). The THQ was calculated according to Wang et al. (2023) using the following equation:

$$\text{THQ} = (\text{EF} \times \text{ED} \times \text{FIR} \times \text{C}) / (\text{RfD} \times \text{BW} \times \text{AT}) \times 10^{-3}$$

where EF represents exposure frequency (365 days/year), ED is the exposure duration (70 years, assuming lifetime adult exposure), FIR is the food ingestion rate (g/person/day,

with values of 50, 75, or 150 g depending on the scenario assessed), C is the concentration of the element in the sample (mg/kg wet weight), RfD is the oral reference dose (g/day), BW is body weight (70 kg), and AT is the averaging time in days (25,550 days). The factor 10^{-3} converts the units appropriately.

The Total Target Hazard Quotient (TTHQ) was calculated by summing the individual THQ values of all analyzed metals, representing the cumulative risk of simultaneous exposure to multiple contaminants:

$$\text{TTHQ} = \sum \text{THQ}$$

According to criteria established by USEPA (2000), THQ or TTHQ values below 1.0 indicate no significant risk of adverse effects on human health. Values between 1.0 and 10.0 indicate potential risk, while values above 10.0 represent a high risk of chronic toxicity.

For arsenic (As), the carcinogenic risk (CR) was also calculated, estimating the risk of cancer development over a lifetime due to chronic exposure. The CR was calculated by the equation:

$$\text{CR} = (\text{EF} \times \text{ED} \times \text{FRI} \times \text{C} \times \text{CSF}) / (\text{BW} \times \text{AT}) \times 10^{-3}$$

where CSF (Cancer Slope Factor) = 1.5 (mg/kg/day) for inorganic arsenic. CR values below 10^{-6} are considered negligible, values between 10^{-6} and 10^{-4} indicate acceptable risk, and values above 10^{-4} represent a high risk of cancer development (USEPA, 2000).

The analyses were conducted considering both the average concentrations (WANG et al., 2023) and the maximum concentrations detected (VAROL and SÜNBÜL, 2020) for each metal in both species, enabling the evaluation of different exposure scenarios.

3 RESULTS

The total length of the specimens ranged from 100 to 155 cm for *A. solandri* and from 25 to 70 cm for *T. albacares*. For *A. solandri*, the highest average and maximum concentrations were observed for Zn, followed by Fe, Al, and Cr. In *T. albacares*, Zn also showed the highest average and maximum concentrations, followed by Fe, Al, and Se. No sample showed Hg concentrations above the detection limit. Concentration values for all analyzed elements are presented in Table 2.

Table 2. Mean, standard deviation, and range (minimum – maximum) of element concentrations ($\mu\text{g/g}$ wet weight) in fish muscle samples. <LOD indicate determinations below the limit of detection.

Element	<i>A. solandri</i>	<i>T. albacares</i>
Ag	0.04 ± 0.02 (<LOD – 0.08)	0.03 ± 0.01 (<LOD – 0.06)
Al	6.18 ± 5.93 (<LOD – 22.91)	2.51 ± 1.14 (<LOD – 3.73)
As	0.11 ± 0.11 (0.02 – 0.40)	0.08 ± 0.02 (0.02 – 0.13)
Ba	0.07 ± 0.06 (<LOD – 0.19)	0.19 ± 0.50 (0.01 – 2.29)
Cd	0.09 ± 0.09 (<LOD – 0.36)	0.03 ± 0.02 (<LOD – 0.07)
Cr	2.39 ± 0.00 (<LOD – 2.39)	1.07 ± 1.10 (<LOD – 2.65)
Cu	0.38 ± 0.17 (0.14 – 0.72)	0.51 ± 0.21 (0.27 – 1.18)
Fe	8.10 ± 5.74 (<LOD – 24.34)	16.34 ± 7.63 (6.32 – 31.30)
Hg	<LOD	<LOD
Li	0.12 ± 0.09 (0.03 – 0.40)	0.09 ± 0.05 (0.03 – 0.21)
Mn	0.21 ± 0.10 (0.02 – 0.45)	0.22 ± 0.12 (0.08 – 0.42)
Pb	0.73 ± 0.29 (<LOD – 1.11)	0.18 ± 0.04 (<LOD – 0.21)
Se	1.51 ± 1.05 (<LOD – 4.00)	2.17 ± 0.71 (0.91 – 3.37)
Zn	45.30 ± 31.92 (4.32 – 145.87)	29.04 ± 17.53 (8.93 – 89.72)

Concerning the differences in element concentrations between species, significant differences were observed for Cd, Cu, Fe, Se, and Zn. Differences between Ag and Pb were marginally significant. Results of interspecific comparisons between element concentrations are shown in Table 3.

Table 3. Results of tests for interspecific differences in element concentrations. Significant differences are shown in bold.

Element	t-test	p value
Ag	3.60	0.0578
Al	2.08	0.1489
As	0.00	0.9892
Ba	1.33	0.2491
Cd	10.47	0.0012
Cr	1.00	0.3173
Cu	4.92	0.0265
Fe	11.75	0.0006
Hg	N/A	N/A
Li	3.04	0.0810
Mn	0.02	0.8817
Pb	3.75	0.0528
Se	7.61	0.0058
Zn	6.06	0.0138

Correlation analysis between individual body size and metal concentrations showed that only Se had a significant correlation for *A. solandri* ($r = -0.640$, $p = 0.046$). For *T. albacares*, Al ($r = -0.999$; $p = 0.018$) and Fe ($r = -0.692$; $p = 0.026$) exhibited a significant negative correlation with length (Table 4).

Table 4. Results of correlation tests between element concentrations and body size in the species analyzed. Significant differences are shown in bold.

Element	<i>A. solandri</i>	<i>T. albacares</i>
Ag	$r=0.066 / p=0.857$	$D = -0.308 / p = 0.614$
Al	$D=-0.400 / p=0.750$	$r=-0.999 / \mathbf{p=0.018}$
As	$r=-0.160 / p=0.659$	$r=-0.433 / p=0.211$
Ba	$r=-0.384 / p=0.273$	$D=-0.138 / p=0.705$
Cd	$r=0.251 / p=0.549$	$r=0.000 / p=0.999$
Cr	N/A	$r = -0.145 / p=0.855$
Cu	$r=-0.321 / p=0.366$	$r=-0.094 / p=0.796$
Fe	$r=0.239 / p=0.536$	$r=-0.692 / \mathbf{p=0.026}$
Hg	N/A	N/A
Li	$D=0.110 / p=0.763$	$r=-0.452 / p=0.189$

Mn	r=-0.399 / p=0.253	r=-0.595 / p=0.070
Pb	N/A	N/A
Se	D=-0.640 / p=0.046	r=-0.257 / p=0.473
Zn	D=0.134 / p=0.712	r=-0.378 / p=0.282

Regulatory limits are available only for As, Cd, Hg, and Pb. The comparison of the average concentrations obtained with the Maximum Tolerance Limits (LMT) established by Brazilian legislation (ANVISA IN No. 160/2022), the World Health Organization (WHO, 1992, 1997, 1998, 2011a), and the European Food Safety Authority (EFSA, 2014, 2020) is presented in Table 4. *Acanthocybium solandri* did not comply with the Pb limits, with average and maximum concentrations exceeding the LMT of 0.30 mg/kg. Cadmium in *A. solandri* reached a maximum value above the ANVISA/WHO limit (0.10 mg/kg) but below the EFSA limit (0.50 mg/kg). For *T. albacares*, the observed concentrations remained within the legal limits. It is worth noting that the metal Hg was below the detection limit in both species in our results, and As showed concentrations well below the MTL of 1.00 mg/kg.

Table 5. Maximum Tolerance Limits (MTL) for regulated metals and metalloids and their mean and maximum concentrations in the analysed fish. Values above MTLs are shown in bold.

Regulated element	ANVISA MTL (mg/kg)	WHO MTL (mg/kg)	EFSA MTL (mg/kg)	<i>A. solandri</i> Average (Max)	<i>T. albacares</i> Average (Max)
As	1.00	1.00	-	0.11 (0.40)	0.08 (0.13)
Cd	0.10	0.10	0.50	0.09 (0.36)	0.03 (0.07)
Hg	1.00	1.00	1.00	<LOD	<LOD
Pb	0.30	0.30	0.30	0.73 (1.11)	0.18 (0.21)

In *A. solandri*, Cd, Cr, Pb, Se, and Zn were the main elements associated with risk, exceeding the reference values at all intake levels, with Cr showing the highest concentrations. In *T. albacares*, Cr and Se were the main elements of concern in all scenarios, while Pb and Zn exceeded the limit only when maximum concentrations were considered. Furthermore, Ba, Cd, Cu, and Fe exceeded the safety limit in the 150 g/day scenario for *T. albacares*. Regarding carcinogenic risk due to As ingestion, exceedance was observed only at the maximum concentrations for *A. solandri* (50, 75, and 150 mg/day) and exclusively in the 150 g/day scenario for *T. albacares*. Finally, the TTHQ exceeded the acceptability limit in all scenarios and for both species, based on both average and maximum concentrations.

Table 6. Target hazard quotients (THQ) and total THQ (TTHQ) for Ag, Al, Ba, Cd, Cr, Cu, Fe, Hg, Li, Mn, Pb, Se, and Zn, and carcinogenic risk (CR) for As calculated for *Acanthocybium solandri* and *Thunnus albacares* from the SPSPA. Values calculated with maximum concentrations are shown in bold.

Element	A. <i>solandri</i> (50g)	T. <i>albacares</i> (50g)	A. <i>solandri</i> (75g)	T. <i>albacares</i> (75g)	A. <i>solandri</i> (150g)	T. <i>albacares</i> (150g)
As	5.38E-06 / 1.88E-04*	3.57E-05 / 6.10E-05	8.07E-06 / 2.82E-04*	5.36E-05 / 9.14E-05	1.61E-05 / 5.64E-04*	1.07E-04* / 1.83E-04*
Ag	0.105 / 0.259	0.070 / 0.197	0.158 / 0.388	0.105 / 0.296	0.316 / 0.776	0.209 / 0.592
Al	0.038 / 0.234	0.004 / 0.038	0.057 / 0.351	0.006 / 0.057	0.113 / 0.701	0.012 / 0.114
Ba	0.012 / 0.039	0.037 / 0.457	0.019 / 0.058	0.056 / 0.686	0.037 / 0.116	0.112 / 1.372*
Cd	1.048* / 4.499*	0.310 / 0.915	1.571* / 6.748*	0.464 / 1.372*	3.143* / 13.496*	0.929 / 2.744*
Cr	2.439* / 48.796*	6.551* / 53.980*	3.658* / 73.194*	9.827* / 80.969*	7.316* / 146.388*	19.653* / 161.939*
Cu	0.135 / 0.258	0.183 / 0.421	0.203 / 0.386	0.275 / 0.632	0.406 / 0.773	0.550 / 1.263*
Fe	0.122 / 0.386	0.259 / 0.497	0.183 / 0.580	0.389 / 0.745	0.366 / 1.159*	0.778 / 1.490*
Hg	N/A	N/A	N/A	N/A	N/A	N/A
Li	0.006 / 0.021	0.005 / 0.011	0.010 / 0.031	0.007 / 0.016	0.019 / 0.062	0.014 / 0.032
Mn	0.014 / 0.029	0.014 / 0.027	0.020 / 0.044	0.021 / 0.041	0.041 / 0.088	0.043 / 0.082
Pb	1.241* / 7.517*	0.125 / 1.456*	1.861* / 11.276*	0.188 / 2.184*	3.722* / 22.551*	0.376 / 4.367*
Se	2.286* / 7.136*	3.880* / 6.020*	3.429* / 10.704*	5.821* / 9.029*	6.859* / 21.407*	11.641* / 18.059*
Zn	0.809 / 2.605*	0.519 / 1.602*	1.213* / 3.907*	0.778 / 2.403*	2.427* / 7.814*	1.556* / 4.806*
TTHQ	8.255* / 71.779*	11.957* / 65.621*	12.382* / 107.667*	17.937* / 98.430*	24.765* / 215.332*	35.873* / 196.860*

The oral reference doses (RfD, used in the equations) were obtained from the following protocols: As (WHO, 2011a,b), Ag (Hadrup and Lam, 2014), Al (WHO, 1997), Ba (NSCFS, 2004), Cd (WHO, 1992), Cr (EFSA, 2014), Cu (WHO, 1998), Fe (US Institute of Medicine Panel on Micronutrients, 2001), Hg (WHO, 2011a), Li (USEPA, 2008), Mn (US Institute of Medicine Panel on Micronutrients, 2001), Pb (EFSA, 2020), Se (U.S. National Institutes of Health, 2021), and Zn (US Institute of Medicine Panel on Micronutrients, 2001). The cancer risk factor (CRF) for As and the provisional RfD for Cr were taken, respectively, from USEPA (2022) and the US Institute of Medicine Panel on Micronutrients (2001). Values were calculated using both average concentrations and individual maximum concentrations. Asterisks mark values equal to or exceeding the “no apparent risk” level set by USEPA (2022): 1.0 for Ag, Al, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Pb, Se, and Zn; and 1.0×10^{-4} for As.

4 DISCUSSION

This study is the first to evaluate metal and metalloid contamination in *Acanthocybium solandri* and *Thunnus albacares* from the São Pedro and São Paulo Archipelago (SPSPA), a remote Brazilian Marine Protected Area and a geologically unique oceanic setting. A predominance of essential elements (Fe, Cu, Zn, Mn, Se, and Cr) over non-essential ones (Al, As, Ba, Cd, Hg, Pb, Ag, and Li) was observed in both species. In *A. solandri*, the concentrations decreased in the order $Zn > Fe > Al > Cr > Se$, while in *T. albacares* the order was $Zn > Fe > Al > Se > Cr$. This predominance of essential elements aligns with the important role they play in fish metabolism (CHANDRAPALAN and KWONG, 2021).

Statistically significant differences in Cd, Cu, Fe, Se, and Zn between the species ($p < 0.05$) are notable despite considerable dietary overlap. In the SPSPA, approximately 90% of the stomach contents of both species consist of *Cypselurus cyanopterus* (VASKE et al., 2005), and even where feeding strategies diverge, with *T. albacares* acting as a specialist and *A. solandri* as a generalist predator (BAQUE-MENOSCAL et al., 2012), prey composition remains partially shared. The persistence of interspecific differences in elemental profiles across these dietary contexts suggests that bioaccumulation and excretion are governed primarily by species-specific physiological mechanisms rather than by prey composition alone.

Zinc (Zn) concentrations were the most significant in the elemental composition of both species, averaging 45.30 mg/kg in *A. solandri* and 29.04 mg/kg in *T. albacares*, reflecting the essential role of this element as an enzymatic cofactor and in protein synthesis (CHANDRAPALAN and KWONG, 2021). The values found for *T. albacares* are comparable to those reported by Ruelas-Inzunza et al. (2011) for populations in the Eastern Pacific Ocean (24.9 mg/kg), higher than average levels reported for North Atlantic tunas (4.82 mg/kg; BESADA et al., 2006), and much lower than those recorded in the Western Indian Ocean (160 mg/kg; KOJADINOVIC et al., 2007). Considering that Zn integrates essential cellular pathways — including redox regulation, antioxidant defense, and energy metabolism (MARET, 2019) — its elevated levels in muscle tissue may reflect the high metabolic activity characteristic of these pelagic active-swimming species.

Iron (Fe) showed the opposite pattern, with *T. albacares* accumulating significantly higher concentrations (16.34 mg/kg vs. 8.10 mg/kg; $p=0.0006$). This difference aligns with the partial endothermy typical of tunas, which demands a greater

oxygen transport capacity through elevated muscle myoglobin concentrations (BERNAL et al., 2017). Moreover, the myoglobin of endothermic species like *T. albacares* exhibits higher oxygen affinity, as reflected by lower P50 values compared to ectothermic species such as *A. solandri* (MARCINEK et al., 2001). These physiological adaptations support the greater concentrations of Fe observed in *T. albacares*.

Among essential metals, selenium also exhibited marked average concentrations in both species (1.51 mg/kg in *A. solandri*; 2.17 mg/kg in *T. albacares*). Selenium occupies a key threshold position in trace element toxicology, being essential at low concentrations (<3 µg/g), but highly toxic at slightly higher levels (KUMAR et al., 2018). In tunas, selenoneine has been identified as the main organic form of selenium in the blood and tissues, representing an important antioxidant mechanism (YAMASHITA and YAMASHITA, 2010). Studies in Atlantic bluefin tuna (*Thunnus thynnus*) have shown that Hg binds to selenium, forming selenolate complexes in tissues. This represents an endogenous detoxification mechanism that reinforces the protective role of Se against methylmercury toxicity (MANCEAU et al., 2025), although Hg was not quantified in the present study. Selenium toxicity in fish primarily occurs through maternal transfer, where ovarian concentrations can cause embryonic deformities and reproductive impairment (UDDIN et al., 2024). The muscle concentrations observed in our study suggest potential for bioaccumulation, considering that studies have already report the muscle-to-ovary ratio for Se ranging from 0.5:1 to 0.8:1 in the migratory salmonoid *Thymallus arcticus* (BRIX et al., 2021). In humans, exposure to Cr via ingestion is associated with renal disease, male infertility, small intestine carcinoma, and other gastrointestinal disorders (Shin et al., 2023).

Aluminum (Al) was the third most abundant element in both species, and showed average concentrations of 6.18 mg/kg in *A. solandri* and 2.51 mg/kg in *T. albacares*. Previous studies conducted on scombrids from the Canary Islands reported considerably lower values, with 0.51 mg/kg in *A. solandri* and 0.64 mg/kg in *T. albacares* (LOZANO-BILBAO et al., 2023). However, historical analyses of *T. albacares* from the Canary Islands show higher concentrations in past decades, reaching 33.44 mg/kg in the 1990s and 18.93 mg/kg in the 2000s (VÁSQUEZ-DOMÍNGUEZ, 2025). The toxicity of aluminum in aquatic organisms is well documented, with the gills being the primary target organ for exposure and accumulation (NAPOLITANO et al., 2023). In this context, the detection of aluminum in the muscle tissue of the species analyzed in our study warrants attention from a food safety perspective, given that fish consumption is the main route of

aluminum exposure in humans (EFSA, 2008). Chronic aluminum exposure has been linked to several adverse effects in humans, including neurotoxicity, oxidative stress, systemic inflammation, and a heightened risk of cardiovascular diseases (TINKOV et al., 2024; BEHRA et al., 2025).

Among the non-essential elements, chromium (Cr) also emerged as a significant contaminant, showing average concentrations of 2.39 mg/kg in *A. solandri* and 1.07 mg/kg in *T. albacares*. These values exceed those reported in other studies for these species (LOZANO-BILBAO et al., 2021; FRANCO-FUENTES et al., 2023; ALMAFRACHI et al., 2025; YOSUVA et al., 2025), indicating a potential toxicological risk. Chromium toxicity varies depending on its chemical form, with hexavalent chromium [Cr(VI)] being more toxic than trivalent chromium [Cr(III)], due to its ability to cross cell membranes, induce oxidative stress, and cause genotoxic damage (KAMILA et al., 2023). In aquatic organisms, exposure to Cr (VI) leads to preferential tissue distribution in the gills and liver, with lower accumulation in muscle, making the muscle concentrations observed here significant (MIN et al., 2016; RAY et al., 2025).

The origin of Cr in the SPSPA is an important issue because, unlike coastal environments where industrial effluents (tanneries, electroplating, coal combustion) are anthropogenic sources, remote oceanic archipelagos mainly receive contaminants through: (1) long-range atmospheric deposition, (2) transport by ocean currents, (3) upwelling of deep waters enriched with metals, and (4) geogenic processes including weathering of ultramafic rocks and volcanism (ROBINSON et al., 2017; WU et al., 2018; SUJITHA et al., 2020; LIU et al., 2022). SPSPA is geologically unique, composed predominantly of serpentinitized peridotites and dunites from the lower oceanic crust, exposed in the São Paulo tectonic fracture zone (CAMPOS et al., 2010; MOTOKI et al., 2017). These ultramafic formations are naturally enriched in elements such as Cr, Al, Fe, and Mg, due to the dominant presence of mafic minerals and chromite (PROENZA et al., 1999). In this way, the weathering of these rocks, accelerated by wave and current action, can release significant amounts of elements into the water column, which subsequently bioaccumulate in marine organisms via branchial absorption and ingestion of contaminated prey.

Contrary to what is predicted by bioaccumulation, a negative correlation was observed between body length and concentrations of Se in *A. solandri* and of Al and Fe in *T. albacares*. Bioaccumulation patterns can be complex, as shown by Lacerda et al. (2017), who found a positive correlation of Hg in *T. obesus* from the Equatorial Atlantic,

but not in *T. albacares*. Changes related to growth and diet also influence exposure: juvenile tuna (<60 cm) consume smaller prey, while adults prey on larger fish and cephalopods (MARTINS et al., 2024). This shift can impact the bioaccumulation patterns of elements, as documented for Se, which tends to accumulate more in basal invertebrates than in predatory vertebrates (STEWART et al., 2010; MEBANE et al., 2025). Processes such as growth dilution may explain the negative correlations observed between size and metal concentration (TRUDEL and RASMUSSEN, 2006). Moreover, juveniles may have less efficient excretion systems (AMIARD et al., 2006), while iron homeostatic regulation tends to improve with age (GANZ, 2013). It is important to note that the *T. albacares* individuals collected mainly represent juveniles. Future studies encompassing the full range of size classes are necessary to fully characterize the patterns of body length versus concentrations.

Comparisons of observed concentrations with the Maximum Tolerance Limits (MTL) revealed significant non-compliances. *A. solandri* exceeded the MTL for Pb (0.73 vs. 0.30 mg/kg) and showed a maximum Cd concentration above the limit established by ANVISA/ WHO (0.36 vs. 0.10 mg/kg) but below the EFSA limit (0.50 mg/kg). *T. albacares* complied with all regulated elements. Non-conformities for *A. solandri* are significant because the species is among the most frequently caught in the SPSPA (VIANA et al., 2015). Lead is highly neurotoxic, interfering with brain development, cognitive function, and the hematopoietic system in humans, raising concerns for vulnerable populations including children and pregnant women (ATSDR, 2020). Cadmium accumulates in the kidneys and is linked to kidney dysfunction and bone demineralization in cases of chronic exposure (JÄRUP and ÅKESSON, 2009).

In fish, Cd and Pb preferentially accumulate in the gills and metabolic organs, with elevated muscle concentrations potentially indicating chronic exposure (CANLI and ATLI, 2003; KOJADINOVIC et al., 2007; JAYAWEERA et al., 2024). The concentrations of Pb detected in this study, even in a remote oceanic region such as the SPSPA, may reflect long-range atmospheric input resulting from the combustion of fossil fuels, mining, and smelting (VERON et al., 1992; BACON et al., 1996). Although the use of lead in gasoline has been widely discontinued, Pb accumulated in marine compartments over decades persists in the environment for centuries, continuing to circulate within oceanic ecosystems (SANTSCHI et al., 2001; YADAV et al., 2025). Similarly, Cd originating mainly from industrial and metallurgical emissions contributes to the long-range atmospheric input detected in remote oceanic regions, reflecting the

influence of global sources even in isolated systems (NRIAGU and PACYNA, 1988; WHO, 1992).

The non-carcinogenic risk assessment identified Cd, Cr, Pb, Se, and Zn as elements of concern in *A. solandri* (THQ > 1.0 in all scenarios), with chromium reaching a THQ of 146.4 in the 150 g/day scenario. In *T. albacares*, Cr and Se exceeded the threshold in all scenarios, while Ba, Cd, Cu, Fe, Pb, and Zn exceeded the threshold only at maximum concentrations or in the high consumption scenario. The TTHQ substantially exceeded the acceptability limit in all scenarios, indicating a high cumulative risk even at moderate consumption (50 g/day). The carcinogenic risk of arsenic exceeded 10^{-4} only at maximum concentrations and in high consumption scenarios. Inorganic arsenic is classified as carcinogenic (Group 1, IARC), with strong evidence linking it to cancers of the skin, lung, bladder, and liver (IARC, 2012). Although arsenic in marine organisms occurs predominantly as arsenobetaine—an organic form considered non-toxic—fractions of inorganic arsenic may be present (FRANCESCONI and KUEHNELT, 2004).

These results reveal limitations of the current regulatory frameworks. Brazilian legislation and international guidelines establish maximum tolerable limits (MTLs) only for As, Cd, Hg, and Pb, ignoring contamination by other metals and metalloids, which presented significant risks in this study. Chromium, the element contributing most to the THQ (>100 times the safety threshold), is still not regulated in fishery products. This gap is especially concerning given that *T. albacares* met all established MTLs but presented a TTHQ greater than 35, demonstrating that legal compliance does not ensure food safety. Moreover, it is important to consider that fishing communities and coastal populations may consume more than 150 g/day, placing them in high-risk groups. Therefore, these findings emphasize the urgent need to revise fishery regulatory parameters, broaden the range of monitored elements, and adopt new approaches for cumulative risk assessment.

Finally, we highlight that the human health risk assessment revealed THQ and TTHQ values exceeding safety limits in various consumption scenarios for both species, with Cr, Se, Cd, Pb, and Zn identified as the primary elements linked to non-carcinogenic risk. The carcinogenic risk from arsenic ingestion was identified only in specific high-consumption scenarios, particularly for *A. solandri*. These results reinforce that, even in a remote oceanic region, there is a potential risk associated with fish consumption, especially for populations with high intake. Fishery resources from other remote oceanic regions may also be subject to contamination by metals and metalloids, highlighting the need for similar investigations in different ocean areas.

Looking ahead, future studies should increase the number of individuals and size classes analyzed, as well as include different biological tissues, to deepen the understanding of the mechanisms of bioaccumulation and element distribution. The use of analytical approaches that enable chemical speciation is also recommended. More broadly, the findings underscore the need for ongoing environmental and food monitoring programs in the SPSPA to support fishery management efforts and public policies focused on environmental conservation and human health protection.

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CONSIDERAÇÕES FINAIS

Esta dissertação reúne, pela primeira vez, dados sobre as concentrações de metais e metaloides em *Acanthocybium solandri* e *Thunnus albacares* no Arquipélago de São Pedro e São Paulo (ASPSP), articulando uma perspectiva bibliométrica global com evidências empíricas de uma região oceânica remota e geologicamente singular.

O Capítulo 1 evidenciou o crescimento assimétrico da produção científica global, com *A. solandri* expressivamente sub-representada nos programas internacionais de monitoramento, lacuna estrutural que o Capítulo 2 começa a preencher ao fornecer um perfil elementar das duas espécies na região. Os dados empíricos demonstraram que o isolamento geográfico não confere proteção contra a contaminação: indivíduos de *A. solandri* apresentaram concentrações de chumbo acima dos limites estabelecidos pela ANVISA, OMS e EFSA, e risco cumulativo não carcinogênico (TTHQ) superior ao limiar de segurança em todos os cenários de consumo avaliados. A espécie *T. albacares*, embora em conformidade com os limites regulatórios vigentes, apresentou TTHQ igualmente acima do aceitável, evidenciando que conformidade legal não equivale à segurança alimentar e que os marcos normativos atuais são insuficientes para capturar o risco de exposição cumulativa a múltiplos elementos.

Em conjunto, os resultados reforçam a urgência de ampliar o espectro de elementos monitorados pelas agências regulatórias, de incorporar métricas de risco cumulativo nas normativas vigentes e de estabelecer programas contínuos de vigilância no ASPSP. Ao demonstrar que contaminantes de origem antrópica alcançam predadores pelágicos em uma área oceânica protegida e remota, esta dissertação contribui para o entendimento de que a saúde dos oceanos e a saúde humana são indissociáveis.