

Analisis Bibliometrik: Perkembangan Metodologi dan Pemetaan Geografis Tren Penelitian Depurasi Logam Berat Pada Kekekangan (Bivalvia) Periode Tahun 2000-2025

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Abstrak: *Pencemaran logam berat pada ekosistem perairan menjadi isu global yang mengancam keamanan pangan laut, khususnya pada kelompok bivalvia yang memiliki kemampuan bioakumulasi tinggi (Roy, 2019). Penelitian ini bertujuan untuk memetakan perkembangan metodologi depurasi logam berat pada bivalvia selama periode 2000–2025 melalui analisis bibliometrik. Data sebanyak 3295 dokumen diekstraksi dari basis data Scopus dan dianalisis menggunakan R-package Bibliometrix. Hasil menunjukkan pertumbuhan publikasi tahunan sebesar 10,37%. Teridentifikasi evolusi metodologi yang signifikan, mulai dari penggunaan radiotracer (2000–2009), pendekatan biokimia dan fraksinasi seluler (2010–2015), hingga adopsi biomarker molekuler dan teknik omics (2016–2025). China mendominasi kontribusi global, sementara Indonesia berkontribusi 1,27% dengan tingkat sitasi yang relatif rendah. Tren penelitian saat ini bergeser menuju integrasi antara depurasi, penilaian risiko kesehatan manusia, dan perubahan lingkungan global.*

PENDAHULUAN

Pencemaran logam berat di perairan merupakan salah satu isu lingkungan global yang berdampak signifikan terhadap keamanan pangan laut dan kesehatan manusia. Aktivitas industri, pertambangan, urbanisasi, dan limbah pertanian menjadi sumber utama masuknya logam berat seperti merkuri (Hg), kadmium (Cd), timbal (Pb), dan arsen (As) ke dalam ekosistem perairan (Ghannem *et al.*, 2022). Logam-logam tersebut bersifat toksik, persisten, serta mampu mengalami bioakumulasi dalam organisme akuatik. Kelompok bivalvia diketahui memiliki kemampuan tinggi dalam mengakumulasi logam berat karena sifatnya sebagai filter feeder dan mobilitas yang rendah. Hal ini menjadikan bivalvia tidak hanya sebagai sumber pangan, tetapi juga sebagai bioindikator kualitas lingkungan perairan (Roy, 2019). Akumulasi logam berat dalam jaringan bivalvia berpotensi menimbulkan risiko kesehatan bagi manusia melalui rantai makanan, sehingga diperlukan upaya mitigasi melalui proses depurasi yang efektif (Yen Le, 2016).

Seiring perkembangan ilmu pengetahuan, metodologi penelitian depurasi logam berat mengalami transformasi yang signifikan. Pendekatan awal berbasis analisis kimia dan pelacakan logam berkembang menjadi pendekatan yang lebih kompleks, termasuk biomarker fisiologis, biokimia, serta molekuler seperti analisis hemocyte dan stres oksidatif (Impellitteri *et al.*, 2022). Pendekatan ini memungkinkan evaluasi yang lebih komprehensif terhadap dampak logam berat

pada organisme. Dalam konteks tersebut, analisis bibliometrik menjadi alat penting untuk mengevaluasi perkembangan suatu bidang ilmu secara sistematis dan kuantitatif. Metode ini mampu mengidentifikasi tren penelitian, kontribusi ilmiah, serta evolusi metodologi dalam suatu bidang kajian (Donthu *et al.*, 2021; Rodríguez, 2006). Oleh karena itu, penelitian ini bertujuan untuk menganalisis perkembangan metodologi depurasi logam berat pada bivalvia selama periode 2000–2025 melalui pendekatan bibliometrik.

METODE PENELITIAN

Analisis bibliometrik dalam penelitian ini mengacu pada pendekatan kuantitatif yang telah banyak digunakan untuk mengevaluasi perkembangan literatur ilmiah secara sistematis (Donthu *et al.*, 2021) untuk mengkaji perkembangan metodologi penelitian depurasi logam berat pada kekerangan (Bivalvia) selama periode tahun 2000–2025. Analisis bibliometrik dipilih karena mampu mengidentifikasi pola publikasi, dinamika kolaborasi ilmiah, serta evolusi pendekatan metodologis dalam suatu bidang riset secara sistematis dan objektif. Fokus utama penelitian ini adalah memetakan transisi metodologi penelitian. Data bibliografis diperoleh dari basis data ilmiah internasional bereputasi (Scopus). Rentang waktu publikasi dibatasi dari tahun 2000 hingga 2025 untuk menangkap perkembangan metodologi secara longitudinal. Penelusuran metadata dilakukan pada tanggal 27 November 2025, dilakukan menggunakan keyword string berikut:

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( ALL ( "deuration" OR "purification" OR "cleaning process" ) AND ALL ( "heavy metal*" OR "metal contamination" OR "toxic metal*" ) AND ALL ( "bivalve*" OR "shellfish" OR "mussel*" OR "clam*" OR "oyster*" ) ) AND PUBYEAR > 1999 AND PUBYEAR < 2026 AND ( LIMIT-TO ( SUBJAREA , "AGRI" ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) AND ( LIMIT-TO ( SRCTYPE , "j" ) )
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Data bibliometrik dianalisis menggunakan software Bibliometrix (R-package). Keandalan data dijaga melalui ekstraksi dari basis data bereputasi dan proses data cleaning. Validitas interpretasi diperkuat dengan membandingkan hasil analisis terhadap literatur kunci.

HASIL PENELITIAN

3.1. Karakteristik Umum Data Bibliometrik

Hasil analisis bibliometrik (Tabel 3.1) menunjukkan bahwa selama periode 2000–2025 terdapat 3295 dokumen ilmiah yang relevan dengan topik bioakumulasi dan depurasi logam berat pada kelompok bivalvia, yang dipublikasikan dalam 541 sumber ilmiah. Laju pertumbuhan publikasi tahunan mencapai 10,37 %, mencerminkan peningkatan minat global yang konsisten terhadap isu kontaminasi logam berat, keamanan pangan laut dan mekanisme depurasi kerang. Rata-rata usia dokumen sebesar 6,97 tahun menunjukkan bahwa bidang ini relatif aktif dan terus berkembang, terutama dalam dekade terakhir. Nilai rata-rata sitasi per dokumen sebesar 23,78 mengindikasikan bahwa publikasi pada bidang ini memiliki tingkat relevansi dan dampak ilmiah yang cukup tinggi, khususnya studi-studi metodologis yang memperkenalkan pendekatan baru dalam analisis bioakumulasi dan depurasi.

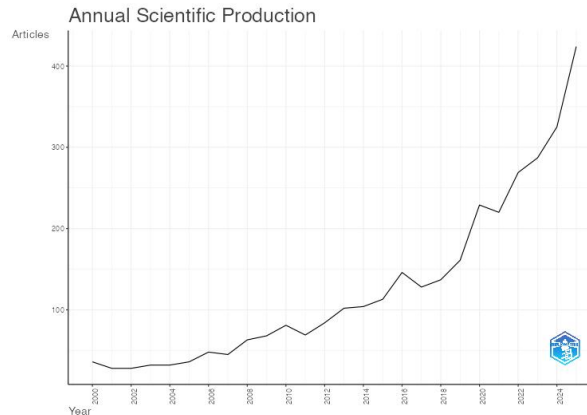
Tabel 1. Data Bibliometrik

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2000: 2025
Sources (Journals, Books, etc)	541
Documents	3295
Annual Growth Rate %	10,37
Document Average Age	6,97
Average citations per doc	23,78
References	25699
DOCUMENT CONTENTS	
Keywords Plus (ID)	16892
Author's Keywords (DE)	8923
AUTHORS	
Authors	15212
Authors of single-authored docs	60
AUTHORS COLLABORATION	
Single-authored docs	63
Co-Authors per Doc	5,71
International co-authorships %	25,55
DOCUMENT TYPES	
Article	3295

3.2. Tren Temporal Penelitian dan Evolusi Metodologi

Analisis tren temporal (Gambar 3.1) memperlihatkan peningkatan signifikan jumlah publikasi sejak pertengahan tahun 2000-an, dengan lonjakan tajam setelah tahun 2010. Hasil analisa bibliometrik (Tabel 3.2) menunjukkan bahwa fase awal (2000–2009), penelitian depurasi logam berat pada bivalvia didominasi oleh pendekatan radiotracer, khususnya penggunaan isotop radioaktif seperti kadmium-109 (^{109}Cd), seng-65 (^{65}Zn), merkuri-203 (^{203}Hg) dan cesium-134 (^{134}Cs) untuk melacak jalur masuk, laju akumulasi, dan kinetika eliminasi logam berat dalam jaringan organisme. Pendekatan radiotracer pada periode ini terbukti sangat efektif dalam memisahkan kontribusi jalur paparan (air, pakan dan sedimen), sehingga menghasilkan pemahaman mendasar mengenai mekanisme fisiologis depurasi. Namun, keterbatasan biaya, regulasi keselamatan radiasi, serta kompleksitas teknis mendorong pengembangan metode alternatif pada periode selanjutnya (Schrope, 2010).

Memasuki periode 2010–2015, terjadi pergeseran metodologi menuju pendekatan biokimia dan seluler, seperti analisis distribusi logam pada fraksi sitosolik, granula, dan berikatan dengan protein pengikat logam (metallothionein). Metode ini memungkinkan evaluasi kapasitas detoksifikasi internal bivalvia serta kaitannya dengan efisiensi depurasi, terutama pada spesies yang memiliki nilai ekonomi tinggi (Impellitteri *et al.*, 2022). Pada periode 2016–2025, tren penelitian semakin mengarah pada pendekatan biomarker molekuler, termasuk analisis stres oksidatif, ekspresi gen terkait detoksifikasi, proteomik, metabolomik dan bioimaging seluler. Pendekatan ini tidak hanya menilai keberhasilan depurasi berdasarkan penurunan konsentrasi logam, tetapi juga menilai dampak biologis residual dan potensi risiko subletal (Kosoy & Biggins, 2022).



Gambar 3.1. Annual Scientific Production

Tabel 2. Tren Penelitian Depurasi Keckerangan (Bivalvia)

Year	Author	Title
2000	Wang, Wenxiong	modeling radiocesium bioaccumulation in a marine food chain
2001	Wang, Wenxiong	bioaccumulation of cd, se, and zn in an estuarine oyster (<i>crassostrea rivularis</i>) and a coastal oyster (<i>saccostrea glomerata</i>)
2002	Bustamante, Paco	biokinetics of zinc and cadmium accumulation and depuration at different stages in the life cycle of the cuttlefish <i>sepia officinalis</i>
2002	Teyssié, Jean-Louis Louis	biokinetics of zinc and cadmium accumulation and depuration at different stages in the life cycle of the cuttlefish <i>sepia officinalis</i>
2002	Warnau, Michel	biokinetics of zinc and cadmium accumulation and depuration at different stages in the life cycle of the cuttlefish <i>sepia officinalis</i>
2002	Wang, Wenxiong	dominance of dietary intake of cadmium and zinc by two marine predatory gastropods
2003	Teyssié, Jean-Louis Louis	relative importance of dissolved and food pathways for lead contamination in shrimp
2003	Yap, Chee Kong	can the shell of the green-lipped mussel <i>perna viridis</i> from the west coast of peninsular malaysia be a potential biomonitoring material for cd, pb and zn?
2003	Yap, Chee Kong	accumulation, depuration and distribution of cadmium and zinc in the green-lipped mussel <i>perna viridis</i> (linnaeus) under laboratory conditions
2003	Wang, Wenxiong	bioavailability of iron complexed with organic colloids to the cyanobacteria <i>synechococcus</i> and <i>trichodesmium</i>
2004	Bustamante, Paco	uptake, transfer and distribution of silver and cobalt in tissues of the common cuttlefish <i>sepia officinalis</i> at different stages of its life cycle
2004	Teyssié, Jean-Louis Louis	uptake, transfer and distribution of silver and cobalt in tissues of the common cuttlefish <i>sepia officinalis</i> at different stages of its life cycle
2004	Warnau, Michel	uptake, transfer and distribution of silver and cobalt in tissues of the common cuttlefish <i>sepia officinalis</i> at different stages of its life cycle
2004	Wang, Wenxiong	temperature influences on the accumulation and elimination of mercury in a freshwater cladoceran, <i>daphnia magna</i>
2004	Wang, Wenxiong	detoxification and effects of ag, cd, and zn pre-exposure on metal uptake kinetics in the clam <i>ruditapes philippinarum</i>
2006	Bustamante, Paco	composition in essential and non-essential elements of early stages of cephalopods and dietary effects on the elemental profiles of <i>octopus vulgaris</i> paralarvae
2006	Bustamante, Paco	contrasting bioaccumulation and transport behaviour of two artificial radionuclides (241am and 134cs) in cuttlefish eggshell
2006	Bustamante, Paco	assessment of the exposure pathway in the uptake and distribution of americium and cesium in cuttlefish (<i>sepia officinalis</i>) at different stages of its life cycle
2006	Bustamante, Paco	subcellular distribution of ag, cd, co, cu, fe, mn, pb, and zn in the digestive gland of the common cuttlefish <i>sepia officinalis</i>
2006	Bustamante, Paco	metal influence on metallothionein synthesis in the hydrothermal vent mussel <i>bathymodiolus thermophilus</i>
2006	Teyssié, Jean-Louis Louis	contrasting bioaccumulation and transport behaviour of two artificial radionuclides (241am and 134cs) in cuttlefish eggshell
2006	Teyssié, Jean-Louis Louis	assessment of the exposure pathway in the uptake and distribution of americium and cesium in cuttlefish (<i>sepia officinalis</i>) at different stages of its life cycle
2006	Warnau, Michel	contrasting bioaccumulation and transport behaviour of two artificial radionuclides (241am and 134cs) in cuttlefish eggshell
2006	Warnau, Michel	assessment of the exposure pathway in the uptake and distribution of americium and cesium in cuttlefish (<i>sepia officinalis</i>) at different stages of its life cycle
2006	Yap, Chee Kong	biomonitoring of ambient concentrations of cadmium, copper, lead and zinc in the coastal wetland water by using gills of the green-lipped mussel <i>perna viridis</i>
2007	Bustamante, Paco	interspecific comparison of cd bioaccumulation in european pectinidae (<i>chlamys varia</i> and <i>pecten maximus</i>)

2007	Teyssié, Jean-Louis Louis	interspecific comparison of cd bioaccumulation in european pectinidae (<i>chlamys varia</i> and <i>pecten maximus</i>)
2007	Warnau, Michel	interspecific comparison of cd bioaccumulation in european pectinidae (<i>chlamys varia</i> and <i>pecten maximus</i>)
2007	Yap, Chee Kong	the distribution of the heavy metals (cu, pb and zn) in the soft and hard tissues of the green-lipped mussel <i>perna viridis</i> (linnaeus) collected from pasir panjang, peninsular Malaysia
2007	Wang, Wenxiong	metallothionein turnover, cytosolic distribution and the uptake of cd by the green mussel <i>perna viridis</i>
2007	Metian, Marc	interspecific comparison of cd bioaccumulation in european pectinidae (<i>chlamys varia</i> and <i>pecten maximus</i>)
2008	Bustamante, Paco	investigation of ag in the king scallop <i>pecten maximus</i> using field and laboratory approaches
2008	Bustamante, Paco	bioaccumulation and detoxification processes of hg in the king scallop <i>pecten maximus</i> : field and laboratory investigations
2008	Bustamante, Paco	metal and metalloid concentrations in the giant squid <i>architeuthis dux</i> from iberian waters
2008	Bustamante, Paco	first experiments on the maternal transfer of metals in the cuttlefish <i>sepia officinalis</i>
2008	Bustamante, Paco	differential bioaccumulation behaviour of ag and cd during the early development of the cuttlefish <i>sepia officinalis</i>
2008	Bustamante, Paco	the tropical brown alga <i>lobophora variegata</i> as a bioindicator of mining contamination in the new caledonia lagoon: a field transplantation study
2008	Teyssié, Jean-Louis Louis	the brown alga <i>lobophora variegata</i> , a bioindicator species for surveying metal contamination in tropical marine environments
2008	Teyssié, Jean-Louis Louis	assimilation and retention of metals in teleost and elasmobranch fishes following dietary exposure
2008	Teyssié, Jean-Louis Louis	first experiments on the maternal transfer of metals in the cuttlefish <i>sepia officinalis</i>
2008	Teyssié, Jean-Louis Louis	differential bioaccumulation behaviour of ag and cd during the early development of the cuttlefish <i>sepia officinalis</i>
2008	Warnau, Michel	investigation of ag in the king scallop <i>pecten maximus</i> using field and laboratory approaches
2008	Warnau, Michel	bioaccumulation and detoxification processes of hg in the king scallop <i>pecten maximus</i> : field and laboratory investigations
2008	Warnau, Michel	the brown alga <i>lobophora variegata</i> , a bioindicator species for surveying metal contamination in tropical marine environments
2008	Warnau, Michel	first experiments on the maternal transfer of metals in the cuttlefish <i>sepia officinalis</i>
2008	Warnau, Michel	differential bioaccumulation behaviour of ag and cd during the early development of the cuttlefish <i>sepia officinalis</i>
2008	Warnau, Michel	the tropical brown alga <i>lobophora variegata</i> as a bioindicator of mining contamination in the new caledonia lagoon: a field transplantation study
2008	Wang, Wenxiong	decoupling of cadmium biokinetics and metallothionein turnover in a marine polychaete after metal exposure
2008	Wang, Wenxiong	bioaccessibility of essential and non-essential metals in commercial shellfish from western europe and asia
2008	Metian, Marc	investigation of ag in the king scallop <i>pecten maximus</i> using field and laboratory approaches
2008	Metian, Marc	bioaccumulation and detoxification processes of hg in the king scallop <i>pecten maximus</i> : field and laboratory investigations
2008	Metian, Marc	the brown alga <i>lobophora variegata</i> , a bioindicator species for surveying metal contamination in tropical marine environments
2009	Bustamante, Paco	bioaccumulation of inorganic hg by the juvenile cuttlefish <i>sepia officinalis</i> exposed to 203hg radiolabelled seawater and food
2009	Bustamante, Paco	bioaccumulation of essential metals (co, mn and zn) in the king scallop <i>pecten maximus</i> : seawater, food and sediment exposures
2009	Bustamante, Paco	delineation of heavy metal uptake pathways (seawater and food) in the variegated scallop <i>chlamys varia</i> , using radiotracer techniques
2009	Bustamante, Paco	phenoloxidase activation in the embryo of the common cuttlefish <i>sepia officinalis</i> and responses to the ag and cu exposure
2009	Bustamante, Paco	effects of increased pco ₂ and temperature on trace element (ag, cd and zn) bioaccumulation in the eggs of the common cuttlefish, <i>sepia officinalis</i>
2009	Teyssié, Jean-Louis Louis	bioaccumulation of inorganic hg by the juvenile cuttlefish <i>sepia officinalis</i> exposed to 203hg radiolabelled seawater and food
2009	Teyssié, Jean-Louis Louis	effects of increased pco ₂ and temperature on trace element (ag, cd and zn) bioaccumulation in the eggs of the common cuttlefish, <i>sepia officinalis</i>
2009	Warnau, Michel	bioaccumulation of inorganic hg by the juvenile cuttlefish <i>sepia officinalis</i> exposed to 203hg radiolabelled seawater and food
2009	Warnau, Michel	bioaccumulation of essential metals (co, mn and zn) in the king scallop <i>pecten maximus</i> : seawater, food and sediment exposures
2009	Warnau, Michel	delineation of heavy metal uptake pathways (seawater and food) in the variegated scallop <i>chlamys varia</i> , using radiotracer techniques
2009	Yap, Chee Kong	zinc and copper concentrations in two species of intertidal crabs from the middle of the west coast of peninsular Malaysia
2009	Wang, Wenxiong	inter-individual variations in cadmium and zinc biodynamics in the scallop <i>chlamys nobilis</i>
2009	Wang, Wenxiong	acclimation to and recovery from cadmium and zinc exposure by a freshwater cyanobacterium, <i>microcystis aeruginosa</i>
2009	Metian, Marc	bioaccumulation of essential metals (co, mn and zn) in the king scallop <i>pecten maximus</i> : seawater, food and sediment exposures
2009	Metian, Marc	delineation of heavy metal uptake pathways (seawater and food) in the variegated scallop <i>chlamys varia</i> , using radiotracer techniques
2010	Bustamante, Paco	acid phosphatase and cathepsin activity in cuttlefish (<i>sepia officinalis</i>) eggs: the effects of ag, cd, and cu exposure
2010	Bustamante, Paco	contrasting accumulation biokinetics and distribution of 241am, co, cs, mn and zn during the whole development time of the eggs of the common cuttlefish, <i>sepia officinalis</i>
2010	Soares, Amadeu M.V.M.	basal levels of enzymatic biomarkers and energy reserves in porcellionides pruinosus

2010	Teyssié, Jean-Louis Louis	cadmium bioaccumulation and retention kinetics in the chilean blue mussel <i>mytilus chilensis</i> : seawater and food exposure pathways
2010	Teyssié, Jean-Louis Louis	delineation of heavy metal contamination pathways (seawater, food and sediment) in tropical oysters from new caledonia using radiotracer techniques
2010	Teyssié, Jean-Louis Louis	contrasting accumulation biokinetics and distribution of 241am, co, cs, mn and zn during the whole development time of the eggs of the common cuttlefish, <i>sepia officinalis</i>
2010	Warnau, Michel	delineation of heavy metal contamination pathways (seawater, food and sediment) in tropical oysters from new caledonia using radiotracer techniques
2010	Warnau, Michel	metal and metalloid bioconcentration capacity of two tropical bivalves for monitoring the impact of land-based mining activities in the new caledonia lagoon
2010	Warnau, Michel	contrasting accumulation biokinetics and distribution of 241am, co, cs, mn and zn during the whole development time of the eggs of the common cuttlefish, <i>sepia officinalis</i>
2010	Yap, Chee Kong	deuration of gut contents in the intertidal snail <i>nerita lineata</i> is not necessary for the study of heavy metal contamination and bioavailability: a laboratory study
2010	Yap, Chee Kong	spatial distribution and sources of polycyclic aromatic hydrocarbons (pahs) in green mussels (<i>perna viridis</i>) from coastal areas of peninsular malaysia: implications for source identification of perylene
2010	Wang, Wenxiong	nmr-based metabolomic studies on the toxicological effects of cadmium and copper on green mussels <i>perna viridis</i>
2010	Wang, Wenxiong	cadmium accumulation and loss in the pacific oyster <i>crassostrea gigas</i> along the west coast of the usa
2010	Metian, Marc	delineation of heavy metal contamination pathways (seawater, food and sediment) in tropical oysters from new caledonia using radiotracer techniques
2010	Metian, Marc	metal and metalloid bioconcentration capacity of two tropical bivalves for monitoring the impact of land-based mining activities in the new caledonia lagoon
2011	Bustamante, Paco	inter-specific and ontogenic differences in $\delta^{13}C$ and $\delta^{15}N$ values and hg and cd concentrations in cephalopods
2011	Teyssié, Jean-Louis Louis	effects of ocean acidification on trace element accumulation in the early-life stages of squid <i>loligo vulgaris</i>
2011	Yap, Chee Kong	accumulation and depuration of cu and zn in the blood cockle <i>anadara granosa</i> (linnaeus) under laboratory conditions
2011	Wang, Wenxiong	metallothionein-like proteins turnover, cd and zn biokinetics in the dietary cd-exposed scallop <i>chlamys nobilis</i>
2012	Bustamante, Paco	temperature and pco 2 effect on the bioaccumulation of radionuclides and trace elements in the eggs of the common cuttlefish, <i>sepia officinalis</i>
2012	Freitas, Rosa	effects of depuration on the element concentration in bivalves: comparison between sympatric <i>ruditapes decussatus</i> and <i>ruditapes philippinarum</i>
2012	Freitas, Rosa	subcellular partitioning of elements and availability for trophic transfer: comparison between the bivalve <i>cerastoderma edule</i> and the polychaete <i>diopatra neapolitana</i>
2012	Teyssié, Jean-Louis Louis	temperature and pco 2 effect on the bioaccumulation of radionuclides and trace elements in the eggs of the common cuttlefish, <i>sepia officinalis</i>
2012	Yap, Chee Kong	is a mussel processing site a point source of zn contamination? evidence of zn remobilization from boiled mussel, <i>perna viridis</i>
2012	Figueira, Etelvina Maria De Almeida Paula	effects of depuration on the element concentration in bivalves: comparison between sympatric <i>ruditapes decussatus</i> and <i>ruditapes philippinarum</i>
2012	Figueira, Etelvina Maria De Almeida Paula	subcellular partitioning of elements and availability for trophic transfer: comparison between the bivalve <i>cerastoderma edule</i> and the polychaete <i>diopatra neapolitana</i>
2012	Hauser-Davis, R. A.	a novel report of metallothioneins in fish bile: sds-page analysis, spectrophotometry quantification and metal speciation characterization by liquid chromatography coupled to icp-ms
2013	Bustamante, Paco	ocean acidification and temperature rise: effects on calcification during early development of the cuttlefish <i>sepia officinalis</i>
2013	Teyssié, Jean-Louis Louis	ocean acidification and temperature rise: effects on calcification during early development of the cuttlefish <i>sepia officinalis</i>
2013	Yap, Chee Kong	accumulation of heavy metals and antioxidative enzymes of <i>centella asiatica</i> in relation to metals of the soils
2013	Yap, Chee Kong	accumulation of trace metals in mussel <i>perna viridis</i> transplanted from a relatively unpolluted site at kg. sg. melayu to a polluted site at kg. pasir puteh and to an unpolluted site at sg belungkor in the straits of johore, iran
2013	Yap, Chee Kong	assessment of heavy metal pollution in the straits of johore by using transplanted caged mussel, <i>perna viridis</i>
2013	Wang, Wenxiong	spatial variation and subcellular binding of metals in oysters from a large estuary in china
2014	Soares, Amadeu M.V.M.	physiological and biochemical responses of three veneridae clams exposed to salinity changes
2014	Freitas, Rosa	physiological and biochemical responses of three veneridae clams exposed to salinity changes
2014	Soares, Amadeu M.V.M.	separating natural from anthropogenic causes of impairment in zebra mussel (<i>dreissena polymorpha</i>) populations living across a pollution gradient
2014	Soares, Amadeu M.V.M.	tolerance of <i>venerupis philippinarum</i> to salinity: osmotic and metabolic aspects
2014	Freitas, Rosa	tolerance of <i>venerupis philippinarum</i> to salinity: osmotic and metabolic aspects
2014	Teyssié, Jean-Louis Louis	bioconcentration of the anionic surfactant linear alkylbenzene sulfonate (las) in the marine shrimp <i>palaemonetes varians</i> : a radiotracer study
2014	Warnau, Michel	bioconcentration of the anionic surfactant linear alkylbenzene sulfonate (las) in the marine shrimp <i>palaemonetes varians</i> : a radiotracer study
2014	Yap, Chee Kong	concentrations of heavy metals in different tissues of the bivalve <i>polymesoda erosa</i> : its potentials as a biomonitor and food safety concern
2014	Figueira, Etelvina Maria De Almeida Paula	physiological and biochemical responses of three veneridae clams exposed to salinity changes
2014	Figueira, Etelvina Maria De Almeida Paula	tolerance of <i>venerupis philippinarum</i> to salinity: osmotic and metabolic aspects
2014	Metian, Marc	bioconcentration of the anionic surfactant linear alkylbenzene sulfonate (las) in the marine shrimp <i>palaemonetes varians</i> : a radiotracer study

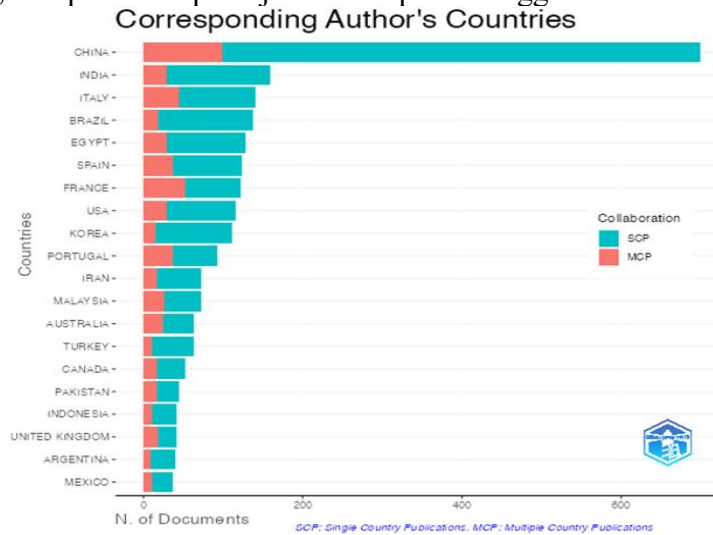
		varians: a radiotracer study
2015	Bustamante, Paco	trace metal concentrations in post-hatching cuttlefish <i>sepia officinalis</i> and consequences of dissolved zinc exposure
2015	Bustamante, Paco	seasonal survey of contaminants (cd and hg) and micronutrients (cu and zn) in edible tissues of cephalopods from tunisia: assessment of risk and nutritional benefits
2015	Soares, Amadeu M.V.M.	spatial distribution and bioaccumulation patterns in three clam populations from a low contaminated ecosystem
2015	Freitas, Rosa	spatial distribution and bioaccumulation patterns in three clam populations from a low contaminated ecosystem
2015	Yap, Chee Kong	lithium levels in peninsular malaysian coastal areas: an assessment based on mangrove snail <i>nerita lineata</i> and surface sediments
2015	Figueira, Etelvina Maria De Almeida Paula	spatial distribution and bioaccumulation patterns in three clam populations from a low contaminated ecosystem
2015	Metian, Marc	seasonal survey of contaminants (cd and hg) and micronutrients (cu and zn) in edible tissues of cephalopods from tunisia: assessment of risk and nutritional benefits
2015	Hauser-Davis, R. A.	trace-elements, methylmercury and metallothionein levels in magellanic penguin (<i>spheniscus magellanicus</i>) found stranded on the southern brazilian coast
2016	Bustamante, Paco	influence of food on the assimilation of essential elements (co, mn, and zn) by turbot <i>scophthalmus maximus</i>
2016	Soares, Amadeu M.V.M.	clam <i>ruditapes philippinarum</i> recovery from short-term exposure to the combined effect of salinity shifts and arsenic contamination
2016	Freitas, Rosa	clam <i>ruditapes philippinarum</i> recovery from short-term exposure to the combined effect of salinity shifts and arsenic contamination
2016	Teyssié, Jean-Louis Louis	influence of food on the assimilation of essential elements (co, mn, and zn) by turbot <i>scophthalmus maximus</i>
2016	Warnau, Michel	influence of food on the assimilation of essential elements (co, mn, and zn) by turbot <i>scophthalmus maximus</i>
2016	Wang, Wenxiong	a comparative proteomic study on the effects of metal pollution in oysters <i>crassostrea hongkongensis</i>
2016	Figueira, Etelvina Maria De Almeida Paula	clam <i>ruditapes philippinarum</i> recovery from short-term exposure to the combined effect of salinity shifts and arsenic contamination
2016	Metian, Marc	influence of food on the assimilation of essential elements (co, mn, and zn) by turbot <i>scophthalmus maximus</i>
2017	Bustamante, Paco	comparative study of trophic transfer of the essential metals co and zn in two tropical fish: a radiotracer approach
2017	Freitas, Rosa	does pre-exposure to warming conditions increase <i>mytilus galloprovincialis</i> tolerance to hg contamination?
2017	Soares, Amadeu M.V.M.	does pre-exposure to warming conditions increase <i>mytilus galloprovincialis</i> tolerance to hg contamination?
2017	Soares, Amadeu M.V.M.	effects of seawater temperature increase on economically relevant native and introduced clam species
2017	Freitas, Rosa	effects of seawater temperature increase on economically relevant native and introduced clam species
2017	Soares, Amadeu M.V.M.	the impacts of emergent pollutants on <i>ruditapes philippinarum</i> : biochemical responses to carbon nanoparticles exposure
2017	Freitas, Rosa	the impacts of emergent pollutants on <i>ruditapes philippinarum</i> : biochemical responses to carbon nanoparticles exposure
2017	Freitas, Rosa	suitability of cholinesterase of polychaete <i>diopatra neapolitana</i> as biomarker of exposure to pesticides: in vitro characterization
2017	Teyssié, Jean-Louis Louis	comparative study of trophic transfer of the essential metals co and zn in two tropical fish: a radiotracer approach
2017	Warnau, Michel	comparative study of trophic transfer of the essential metals co and zn in two tropical fish: a radiotracer approach
2017	Figueira, Etelvina Maria De Almeida Paula	does pre-exposure to warming conditions increase <i>mytilus galloprovincialis</i> tolerance to hg contamination?
2017	Figueira, Etelvina Maria De Almeida Paula	effects of seawater temperature increase on economically relevant native and introduced clam species
2017	Figueira, Etelvina Maria De Almeida Paula	the impacts of emergent pollutants on <i>ruditapes philippinarum</i> : biochemical responses to carbon nanoparticles exposure
2017	Metian, Marc	comparative study of trophic transfer of the essential metals co and zn in two tropical fish: a radiotracer approach
2018	Bustamante, Paco	the role of marine biotoxins on the trophic transfer of mn and zn in fish
2018	Soares, Amadeu M.V.M.	integrated multivariate approach of ecological and ecotoxicological parameters in coastal environmental monitoring studies
2018	Soares, Amadeu M.V.M.	influence of temperature rise on the recovery capacity of <i>mytilus galloprovincialis</i> exposed to mercury pollution
2018	Freitas, Rosa	influence of temperature rise on the recovery capacity of <i>mytilus galloprovincialis</i> exposed to mercury pollution
2018	Freitas, Rosa	biogeochemical dynamics and bioaccumulation processes in manila clam: implications for biodiversity and ecosystem services in the ria de aveiro lagoon
2018	Soares, Amadeu M.V.M.	biogeochemical dynamics and bioaccumulation processes in manila clam: implications for biodiversity and ecosystem services in the ria de aveiro lagoon
2018	Soares, Amadeu M.V.M.	effects of single and combined exposure of pharmaceutical drugs (carbamazepine and cetirizine) and a metal (cadmium) on the biochemical responses of <i>r. philippinarum</i>
2018	Freitas, Rosa	effects of single and combined exposure of pharmaceutical drugs (carbamazepine and cetirizine) and a metal (cadmium) on the biochemical responses of <i>r. philippinarum</i>
2018	Wang, Wenxiong	uniquely high turnover of nickel in contaminated oysters <i>crassostrea hongkongensis</i> : biokinetics and subcellular distribution
2018	Figueira, Etelvina Maria De Almeida Paula	influence of temperature rise on the recovery capacity of <i>mytilus galloprovincialis</i> exposed to mercury pollution
2018	Figueira, Etelvina Maria De Almeida Paula	biogeochemical dynamics and bioaccumulation processes in manila clam: implications for biodiversity and ecosystem services in the ria de aveiro lagoon
2018	Figueira, Etelvina Maria De Almeida Paula	effects of single and combined exposure of pharmaceutical drugs (carbamazepine and cetirizine) and a metal (cadmium) on the biochemical responses of <i>r. philippinarum</i>
2018	Metian, Marc	the role of marine biotoxins on the trophic transfer of mn and zn in fish
2019	Freitas, Rosa	soluble esterases as biomarkers of neurotoxic compounds in the widespread serpulid <i>ficopomatus enigmaticus</i> (fauvel, 1923)

2019	Freitas, Rosa	biochemical and physiological responses induced in <i>mytilus galloprovincialis</i> after a chronic exposure to salicylic acid
2019	Soares, Amadeu M.V.M.	biochemical and physiological responses induced in <i>mytilus galloprovincialis</i> after a chronic exposure to salicylic acid
2019	Soares, Amadeu M.V.M.	the effect of temperature on triclosan and lead exposed mussels
2019	Freitas, Rosa	the effect of temperature on triclosan and lead exposed mussels
2019	Soares, Amadeu M.V.M.	the influence of climate change on the fate and behavior of different carbon nanotubes materials and implication to estuarine invertebrates
2019	Freitas, Rosa	the influence of climate change on the fate and behavior of different carbon nanotubes materials and implication to estuarine invertebrates
2019	Soares, Amadeu M.V.M.	the impacts of warming on the toxicity of carbon nanotubes in mussels
2019	Freitas, Rosa	the impacts of warming on the toxicity of carbon nanotubes in mussels
2019	Figueira, Etelvina Maria De Almeida Paula	the influence of climate change on the fate and behavior of different carbon nanotubes materials and implication to estuarine invertebrates
2019	Figueira, Etelvina Maria De Almeida Paula	the impacts of warming on the toxicity of carbon nanotubes in mussels
2019	Hauser-Davis, R. A.	subcellular metal distributions and metallothionein associations in rough-toothed dolphins (<i>steno bredanensis</i>) from southeastern brazil
2020	Bustamante, Paco	diet variably affects the trophic transfer of trace elements in the oyster <i>crassostrea gigas</i>
2020	Bustamante, Paco	influence of sexual dimorphism on stable isotopes and trace element concentrations in the greater hooked squid <i>moroteuthopsis ingens</i> from new zealand waters
2020	Soares, Amadeu M.V.M.	bioaccumulation and biochemical patterns of <i>ruditapes philippinarum</i> clams: responses to seasonality and low contamination levels
2020	Freitas, Rosa	bioaccumulation and biochemical patterns of <i>ruditapes philippinarum</i> clams: responses to seasonality and low contamination levels
2020	Soares, Amadeu M.V.M.	the role of temperature on the impact of remediated water towards marine organisms
2020	Freitas, Rosa	the role of temperature on the impact of remediated water towards marine organisms
2020	Soares, Amadeu M.V.M.	oxidative stress, metabolic and histopathological alterations in mussels exposed to remediated seawater by go-pei after contamination with mercury
2020	Freitas, Rosa	oxidative stress, metabolic and histopathological alterations in mussels exposed to remediated seawater by go-pei after contamination with mercury
2020	Teyssié, Jean-Louis Louis	diet variably affects the trophic transfer of trace elements in the oyster <i>crassostrea gigas</i>
2020	Warnau, Michel	diet variably affects the trophic transfer of trace elements in the oyster <i>crassostrea gigas</i>
2020	Figueira, Etelvina Maria De Almeida Paula	the role of temperature on the impact of remediated water towards marine organisms
2020	Figueira, Etelvina Maria De Almeida Paula	oxidative stress, metabolic and histopathological alterations in mussels exposed to remediated seawater by go-pei after contamination with mercury
2020	Metian, Marc	diet variably affects the trophic transfer of trace elements in the oyster <i>crassostrea gigas</i>
2020	Hauser-Davis, R. A.	subcellular cadmium, lead and mercury compartmentalization in guiana dolphins (<i>sotalia guianensis</i>) from southeastern brazil
2020	Hauser-Davis, R. A.	the current knowledge gap on metallothionein mediated metal-detoxification in elasmobranchs
2020	Hauser-Davis, R. A.	contamination and oxidative stress biomarkers in estuarine fish following a mine tailing disaster
2020	Hauser-Davis, R. A.	total and subcellular ti distribution and detoxification processes in <i>pontoporia blainvillei</i> and <i>steno bredanensis</i> dolphins from southeastern brazil
2021	Bustamante, Paco	a multifaceted assessment of the effects of polyethylene microplastics on juvenile gilthead seabreams (<i>sparus aurata</i>)
2021	Soares, Amadeu M.V.M.	cadmium accumulation and kinetics in <i>solea senegalensis</i> tissues under dietary and water exposure and the link to human health
2021	Soares, Amadeu M.V.M.	how does <i>mytilus galloprovincialis</i> respond when exposed to the gametophyte phase of the invasive red macroalga <i>asparagopsis armata</i> exudate?
2021	Metian, Marc	a multifaceted assessment of the effects of polyethylene microplastics on juvenile gilthead seabreams (<i>sparus aurata</i>)
2021	Hauser-Davis, R. A.	interactions between mercury and environmental factors: a chemometric assessment in seafood from an eutrophic estuary in southeastern brazil
2021	Hauser-Davis, R. A.	lead and cadmium contamination in sediments and blue crabs <i>callinectes danae</i> from a Ramsar wetland in southeastern brazil; contaminação de chumbo e cádmio em sedimentos e siris <i>callinectes danae</i> provenientes de uma zona úmida de importância internacional Ramsar no sudeste do Brasil.
2022	Freitas, Rosa	ecotoxicity of copper(II) chloride in grooved carpet shell (<i>ruditapes decussatus</i>)
2022	Yap, Chee Kong	comparative study of potentially toxic nickel and their potential human health risks in seafood (fish and mollusks) from peninsular Malaysia
2022	Hauser-Davis, R. A.	toxic metal and metalloid contamination in seafood from an eutrophic Brazilian estuary and associated public health risks
2022	Hauser-Davis, R. A.	baseline titanium levels of three highly consumed invertebrates from an eutrophic estuary in southeastern Brazil
2022	Hauser-Davis, R. A.	mercurial contamination: a consumer health risk assessment concerning seafood from a eutrophic estuary in southeastern Brazil
2022	Hauser-Davis, R. A.	oxidative stress and metal homeostasis alterations in <i>Danio rerio</i> (zebrafish) under single and combined carbamazepine, acetaminophen and cadmium exposures
2023	Yap, Chee Kong	lower health risks of potentially toxic metals after transplantation of aquacultural farmed mussels from a polluted site to unpolluted sites: a biomonitoring study in the straits of Johore
2023	Yap, Chee Kong	byssus of green-lipped mussel <i>Perna perna</i> as a biomonitoring biopolymer for zinc pollution in coastal waters
2023	Wang, Wenxiong	bioimaging tools reveal copper processing in fish cells by mitophagy

2024	Soares, Amadeu M.V.M.	trace elements assessment in cerastoderma glaucum from port areas in the tunisian mediterranean coast: the influence of parasites on bioaccumulation
2024	Freitas, Rosa	trace elements assessment in cerastoderma glaucum from port areas in the tunisian mediterranean coast: the influence of parasites on bioaccumulation
2024	Teyssié, Jean-Louis Louis	maternal transfer of trace elements to shark eggs and their dietary assimilation efficiencies
2024	Yap, Chee Kong	human health risk, potentials of biomonitoring and phytoremediation of copper using amaranthus viridis
2025	Soares, Amadeu M.V.M.	breaking new ground: gadolinium and microplastics co-exposure and biochemical alterations in marine clam donax trunculus
2025	Freitas, Rosa	breaking new ground: gadolinium and microplastics co-exposure and biochemical alterations in marine clam donax trunculus
2025	Yap, Chee Kong	zinc bioaccumulation and detoxification mechanisms in pomacea insularum: implications for biomonitoring in metal-contaminated ecosystems
2025	Yap, Chee Kong	the potentials of perna viridis shells as biomonitoring tools for cadmium contamination in coastal area of peninsular Malaysia

3.3. Distribusi Geografis dan Pola Kolaborasi Internasional

Analisis distribusi geografis dan pola kolaborasi internasional (Gambar 3.2 dan Tabel 3.3) menunjukkan bahwa China (21,24 %) menjadi kontributor terbesar publikasi, diikuti oleh India, Italia, Brasil, Prancis, dan Spanyol. Dominasi negara-negara tersebut berkorelasi dengan tingginya tekanan antropogenik di wilayah pesisir serta pentingnya bivalvia sebagai komoditas perikanan dan indikator lingkungan. Persentase kolaborasi internasional sebesar 25,55 % menunjukkan bahwa penelitian depurasi logam berat bersifat lintas negara dan multidisipliner. Negara-negara Eropa Barat seperti Prancis, Italia dan Portugal menunjukkan tingkat kolaborasi internasional yang relatif tinggi, yang berkontribusi pada kualitas metodologi dan tingginya rata-rata sitasi artikel. Hasil analisis bibliometrik menunjukkan Indonesia hanya menyumbang sekitar 1,27 % publikasi global, namun menunjukkan tren peningkatan kontribusi dalam dekade terakhir, khususnya pada studi biomonitoring dan aspek keamanan pangan. Disisi lain, rendahnya rata-rata sitasi (6,2 sitasi per artikel) mengindikasikan perlunya peningkatan kualitas metodologi, kolaborasi internasional, dan publikasi pada jurnal bereputasi tinggi.



Gambar 3.2 Corresponding Author's Countries

3.4 Perubahan Fokus Penelitian

Hasil analisa bibliometrik (Tabel 3.2) menunjukkan pergeseran fokus penelitian dari studi kinetika dasar menuju pendekatan terintegrasi yang mengaitkan depurasi dengan risiko kesehatan manusia. Studi terbaru tidak hanya mengevaluasi efektivitas depurasi dalam menurunkan konsentrasi logam berat, tetapi juga menilai implikasinya terhadap batas aman konsumsi, paparan

kronis dan dampak perubahan iklim seperti peningkatan suhu dan pengasaman laut (Yen Le, 2016). Integrasi antara analisis logam, biomarker fisiologis, dan indikator molekuler memperkuat posisi bivalvia sebagai model bioindikator sekaligus objek kajian keamanan pangan laut. Pendekatan ini mencerminkan evolusi metodologi yang lebih holistik, sejalan dengan tuntutan pengelolaan sumber daya perikanan yang berkelanjutan.

Tabel 3. Distribusi Geografis Penelitian

No.	Country	Articles	Articles %	SCP	MCP	MCP %
1	China	700	21,24431	601	99	14,142857
2	India	159	4,8254932	129	30	18,867925
3	Italy	140	4,2488619	95	45	32,142857
4	Brazil	137	4,1578149	119	18	13,138686
5	Egypt	128	3,8846738	99	29	22,65625
6	Spain	124	3,7632777	87	37	29,83871
7	France	122	3,7025797	70	52	42,622951
8	Usa	116	3,5204856	87	29	25
9	Korea	111	3,3687405	95	16	14,414414
10	Portugal	92	2,7921093	55	37	40,217391
11	Iran	73	2,215478	56	17	23,287671
12	Malaysia	73	2,215478	47	26	35,616438
13	Australia	64	1,9423369	40	24	37,5
14	Turkey	64	1,9423369	54	10	15,625
15	Canada	53	1,6084977	36	17	32,075472
16	Pakistan	45	1,3657056	28	17	37,777778
17	Indonesia	42	1,2746586	31	11	26,190476
18	United Kingdom	42	1,2746586	23	19	45,238095
19	Argentina	40	1,2139606	31	9	22,5
20	Mexico	37	1,1229135	27	10	27,027027
21	Poland	36	1,0925645	32	4	11,111111
22	Tunisia	35	1,0622155	18	17	48,571429
23	Germany	33	1,0015175	16	17	51,515152
24	Hong Kong	32	0,9711684	20	12	37,5
25	Thailand	29	0,8801214	19	10	34,482759
26	Belgium	28	0,8497724	17	11	39,285714
27	Japan	28	0,8497724	18	10	35,714286
28	Algeria	22	0,6676783	14	8	36,363636
29	Morocco	22	0,6676783	17	5	22,727273
30	New Zealand	22	0,6676783	17	5	22,727273
31	Saudi Arabia	21	0,6373293	7	14	66,666667
32	Chile	20	0,6069803	16	4	20
33	Nigeria	20	0,6069803	17	3	15
34	Norway	18	0,5462823	7	11	61,111111
35	Croatia	16	0,4855842	11	5	31,25
36	Monaco	16	0,4855842	1	15	93,75
37	Netherlands	15	0,4552352	13	2	13,333333
38	Bangladesh	14	0,4248862	5	9	64,285714
39	Czech Republic	14	0,4248862	10	4	28,571429
40	Greece	14	0,4248862	9	5	35,714286
41	Denmark	13	0,3945372	8	5	38,461539
42	South Africa	13	0,3945372	9	4	30,769231
43	Philippines	12	0,3641882	12	0	0
44	Ireland	11	0,3338392	5	6	54,545455
45	Sweden	10	0,3034901	3	7	70
46	Iraq	9	0,2731411	9	0	0
47	Israel	9	0,2731411	4	5	55,555556
48	Colombia	8	0,2427921	5	3	37,5
49	Serbia	8	0,2427921	8	0	0
50	Austria	7	0,2124431	2	5	71,428571
51	Bulgaria	7	0,2124431	5	2	28,571429
52	Finland	7	0,2124431	2	5	71,428571
53	Hungary	7	0,2124431	6	1	14,285714
54	United Arab Emirates	7	0,2124431	4	3	42,857143
55	Venezuela	7	0,2124431	5	2	28,571429
56	Ukraine	6	0,1820941	3	3	50
57	Romania	5	0,1517451	4	1	20
58	Fiji	4	0,1213961	2	2	50
59	Jordan	4	0,1213961	3	1	25
60	Kenya	4	0,1213961	1	3	75
61	Peru	4	0,1213961	2	2	50
62	Qatar	4	0,1213961	2	2	50
63	Zimbabwe	4	0,1213961	3	1	25
64	Cameroon	3	0,091047	2	1	33,333333
65	Ghana	3	0,091047	3	0	0
66	Kuwait	3	0,091047	1	2	66,666667
67	Singapore	3	0,091047	2	1	33,333333
68	Sri Lanka	3	0,091047	3	0	0
69	Vietnam	3	0,091047	3	0	0
70	Benin	2	0,060698	1	1	50
71	Ecuador	2	0,060698	0	2	100
72	Ethiopia	2	0,060698	0	2	100
73	Kazakhstan	2	0,060698	2	0	0
74	Latvia	2	0,060698	1	1	50
75	Lithuania	2	0,060698	0	2	100
76	Montenegro	2	0,060698	1	1	50
77	Russia	2	0,060698	2	0	0
78	Senegal	2	0,060698	0	2	100
79	Tanzania	2	0,060698	1	1	50
80	Antigua	1	0,030349	1	0	0
81	Azerbaijan	1	0,030349	1	0	0
82	Bosnia	1	0,030349	1	0	0
83	Brunei	1	0,030349	1	0	0
84	Cambodia	1	0,030349	0	1	100
85	Dominican Republic	1	0,030349	0	1	100
86	Estonia	1	0,030349	0	1	100
87	Georgia	1	0,030349	1	0	0
88	Guam	1	0,030349	0	1	100
89	Iceland	1	0,030349	0	1	100
90	Jamaica	1	0,030349	1	0	0
91	Lebanon	1	0,030349	0	1	100
92	Oman	1	0,030349	1	0	0
93	Sudan	1	0,030349	1	0	0
94	Switzerland	1	0,030349	0	1	100
95	Trinidad And Tobago	1	0,030349	1	0	0
96	Uganda	1	0,030349	0	1	100
97	Uruguay	1	0,030349	0	1	100
98	Yemen	1	0,030349	0	1	100

KESIMPULAN

Tema depurasi logam berat pada bivalvia mengalami pertumbuhan yang stabil dan aktif (10,37 % per tahun), menunjukkan urgensi isu keamanan pangan laut. Metodologi penelitian mengalami transformasi dari pelacakan isotop radioaktif (misalnya kadmium-109 (109Cd) dan seng-65 (65Zn)) menuju pendekatan molekuler yang lebih presisi (proteomik dan metabolomik). Orientasi penelitian telah berkembang dari sekadar mengukur penurunan konsentrasi logam menjadi analisis dampak biologis residual dan mitigasi risiko bagi konsumen manusia (Donthu *et al.*, 2021).. Indonesia mengalami peningkatan publikasi, namun masih perlu memperkuat kolaborasi internasional dan kualitas metodologi untuk meningkatkan impact ilmiah di tingkat global.

Penelitian mendatang perlu mengintegrasikan pendekatan bioimaging untuk mendalami mekanisme detoksifikasi seluler serta mengembangkan teknologi depurasi skala industri yang ramah lingkungan. Selain itu, penguatan kolaborasi internasional krusial bagi akademisi Indonesia guna meningkatkan standar metodologi dan dampak ilmiah global. Selain itu, riset ini diharapkan menjadi basis ilmiah dalam pembaruan regulasi keamanan pangan laut.

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