Marine Invertebrates in the Anthropocene: Biodiversity, Stressors, and Emerging Conservation Tools - A Literature Review

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ABSTRACT

Marine invertebrates form the ecological foundation of marine ecosystems, contributing to habitat formation, nutrient cycling, food security, and the blue bioeconomy. However, growing evidence shows that many invertebrate populations are declining due to climate change, pollution, habitat disturbance, exploitation, and emerging industrial activities. Integrating findings from ecology, genomics, toxicology, microbiology, and artificial intelligence (AI), this review synthesizes current knowledge on biodiversity patterns, multiple stressor impacts, molecular insights, and management tools relevant to conservation. Taxonomic inventories reveal high but unevenly documented biodiversity, while long-term datasets indicate severe declines among several taxa, including endemic species at high extinction risk. Multiple stressor experiments show complex responses, often antagonistic rather than additive. Advances in barcoding, environmental DNA (eDNA), holobiont studies, and stem-cell technologies offer new opportunities for monitoring and restoration. Emerging AI and geospatial planning tools enable integrative conservation frameworks at broader scales. This review highlights major knowledge gaps and emphasizes the need for cross-disciplinary approaches aligned with ethical, welfare, and sustainable-use perspectives to secure marine invertebrate resilience in the Anthropocene.

Keywords: marine invertebrates; biodiversity loss; multiple stressors; eDNA; conservation tools; blue bioeconomy; climate change

INTRODUCTION

Marine invertebrates—bivalves, gastropods, echinoderms, cnidarians, sponges, crustaceans and myriad other taxa—are central to the functioning and resilience of marine ecosystems. They construct and engineer habitats, regulate biogeochemical cycles, support fisheries and aquaculture, and contribute to cultural practices and emerging blue bioeconomy sectors. Yet, contemporary evidence indicates that many marine invertebrate populations and assemblages are declining, often rapidly, under the combined influence of climate change, pollution, habitat modification, industrialisation and exploitation (Johnson et al., 2025; Wang et al., 2024).

Synthesizing recent advances across genetics, ecology, toxicology, and conservation science, this review reassesses

the status and future of marine invertebrates by integrating 21st-century evidence from long-term monitoring, multi-stressor experiments, and novel molecular and computational tools. Large-scale time series reveal severe but taxon-specific declines, with macroalgae and mobile reef invertebrates showing high extinction risk and marked regional endemism, while iconic species such as the live-bearing sea star *Parvulastra vivipara* now qualify as Critically Endangered (Johnson et al., 2025; Strain et al., 2024). Climate-driven warming, ocean acidification, hypoxia and changing circulation patterns interact with local stressors including contaminants, noise, aquaculture, and coastal development, often producing non-additive responses in bivalves and other taxa (Rynkowski et al., 2025; Gianni et al., 2025; Vásquez et al., 2025).

In parallel, high-resolution genomic, barcoding, and environmental DNA approaches are uncovering cryptic diversity, revealing new biogeographic patterns, and resolving taxonomic bottlenecks from coastal wetlands to coral reefs (Ghazali et al., 2025; Xu et al., 2024; Boco et al., 2025). Holobiont and microbiome perspectives, together with advances in cell lines and stem-cell-based technologies, are transforming our understanding of invertebrate physiology, stress responses, and restoration potential (Zhou et al., 2024; Rinkevich & Pomponi, 2025; Hutchinson et al., 2024). Deep learning, AI-assisted monitoring, weight-of-evidence risk frameworks and geospatial conservation planning now enable integrated assessment at scales relevant to management (Nilsson et al., 2025; Piccardo et al., 2024; Cobb et al., 2023).

Recent decades have seen an explosion of research on invertebrate conservation, spanning long-term ecological monitoring, multi-stressor experiments, global bibliometric syntheses, and emerging molecular and computational technologies (Idamokoro & Niba, 2024; Nilsson et al., 2025). Regional reviews and inventories highlight both extraordinary diversity and persistent knowledge gaps in macrozoobenthos and benthic macroinvertebrates from coral reefs, wetlands, lagoons and soft-sediment systems (Aulia et al., 2024; Sahidjan et al., 2025; Belart et al., 2025; Vicente et al., 2024; Komendić et al., 2024). Parallel work reveals biases in geography, taxa and methods that continue to limit management-relevant knowledge, especially in the Global South (Idris et al., 2025; Garcia & Anticamara, 2023).

This review builds on these foundations to provide an updated, integrated perspective on marine invertebrates in the Anthropocene. We (i) re-evaluate conservation status, diversity patterns and monitoring trends; (ii) synthesize current understanding of interacting global and local stressors; (iii) highlight advances in molecular, microbiome and cell-based approaches; (iv) review AI-enabled and integrative risk assessment tools; and (v) discuss governance, ethics and sustainable-use implications, including emerging blue-bioresource applications. Throughout, we focus on recent literature and case studies spanning temperate and tropical systems, nearshore and offshore habitats, and a broad spectrum of taxa, with summary tables that anchor our discussion in concrete examples.

MATERIALS & METHODS
This review employed a qualitative synthesis of peer-reviewed literature spanning ecology, molecular biology, toxicology, conservation planning, and computational science. Publications were identified primarily through keyword searches in major bibliographic databases (e.g., Scopus, Web of Science, and Google Scholar) using combinations of terms such as "marine invertebrates", "biodiversity", "multiple stressors", "ocean acidification", "environmental DNA", "holobiont", "artificial intelligence", and "conservation planning". The time window focused on studies published between 1990 and 2025,

with emphasis on articles and reviews from the last decade.

Long-term datasets, experimental studies, taxonomic syntheses, case studies, and theoretical frameworks were screened for relevance to four core themes: (i) patterns and trends in biodiversity and conservation status; (ii) impacts of global and local stressors, including multi-stressor interactions; (iii) molecular, genomic, and microbiome innovations; and (iv) AI-enabled monitoring, risk assessment, and spatial planning. Key themes were identified through thematic coding, and findings were organised into sections corresponding to these themes.

RESULT
Global Diversity, Conservation Status, and Monitoring
Taxonomic Inventories and Knowledge Gaps

Global syntheses show that research on invertebrate conservation has increased markedly since the 1990s, with strong growth in publications addressing biodiversity, coral reefs, climate change and marine protected areas (MPAs) (Idamokoro & Niba, 2024). Bibliometric analyses indicate that scientific output is concentrated in economically and scientifically advanced nations, with the USA, Australia and several European countries dominating citation networks, while many biodiverse regions remain under-represented (Idamokoro & Niba, 2024; Wang et al., 2024).

Taxonomic inventories underscore both the richness and incompleteness of current knowledge. For marine molluscs in the Philippines, a megadiverse hotspot, a synthesis of literature, museum records and databases documents over 8,000 marine species, yet reveals large fractions of species with unresolved taxonomy or unknown conservation status (Garcia & Anticamara, 2023). Across ASEAN countries, >18,000 benthic macroinvertebrate species from six major phyla have been reported, but coverage is highly uneven, and several nations rely heavily on foreign taxonomists, raising risks of misidentification and under-representation of local expertise (Idris et al., 2025). Global reviews of benthic foraminifera in coastal lagoons similarly highlight geographic gaps and "Linnean, Wallacean, Hutchinsonian and Prestonian" shortfalls in species discovery, distribution, tolerance and population dynamics (Belart et al., 2025).

Regional assessments of macrozoobenthos in Java coral reefs (Indonesia) and macroalgae-associated invertebrates in Brazilian MPAs illustrate these issues at finer scales (Aulia et al., 2024; Vicente et al., 2024). In Java, 482 macrozoobenthic species across four phyla have been reported, with strong spatial biases favouring northern coastal sites and limited monitoring in areas with moderate to good coral cover (Aulia et al., 2024). In the Alcatrazes archipelago, macroalgae beds host at least 91 invertebrate species, 73 of them new records for the area, demonstrating the hidden biodiversity associated with structurally complex habitats and the value of targeted inventories within MPAs (Vicente et al., 2024).

Large-scale assessments indicate that marine invertebrate research has grown significantly since the 1990s, with notable biases in geography and methodology. Biodiversity-rich areas such as Southeast Asia remain under-documented, and taxonomic expertise is unevenly distributed. Several inventories across Indonesia, the Philippines, Brazil, and ASEAN nations highlight substantial species richness but also unresolved taxonomy, limited monitoring, and reliance on foreign specialists.

Table 1. Recent studies on diversity, status and monitoring of marine invertebrates

Focal group / system	Region / habitat	Main approach	Key conservation insight	Ref.
Macroalgae & mobile reef invertebrates	Australian temperate reefs	30-year monitoring	High extinction risk and endemism; major Red List gaps	Johnson et al., 2025
Parvulastra vivipara sea star	SE Tasmania intertidal	Historical vs recent surveys	>90% density decline; qualifies as Critically Endangered	Strain et al., 2024
Soft-sediment macrofauna	Subarctic Placentia Bay, Canada	20-year resurvey	Community reorganization with functional shifts linked to sediment changes	Komendić et al., 2024
Macrozoobenthos of Java coral reefs	Java, Indonesia	Literature review & collation	482 species; spatial biases; need for expanded monitoring	Aulia et al., 2024
Macroalgae-associated invertebrates	Alcatrazes MPA, Brazil	Field sampling & inventories	91 species; many new records; invasive species detected	Vicente et al., 2024
Benthic macroinvertebrates in ASEAN	ASEAN coastal systems	Regional synthesis	>18,000 species; taxonomic capacity gaps and reliance on foreign experts	Idris et al., 2025
Philippine marine molluscs	Philippines, multiple habitats	Taxonomic synthesis	>7,000 marine species; numerous unresolved taxa and unknown conservation status	Garcia & Anticamara, 2023
Invertebrates & conservation bibliometrics	Global	Bibliometric analysis	Strong growth in invertebrate conservation research; geographic and thematic biases	Idamokoro & Niba, 2024

Long-Term Monitoring and Extinction Risk

Long-term ecological datasets, though still rare for invertebrates, are transforming our understanding of population trajectories and extinction risk. Using >30 years of standardized monitoring at Australian reefs, Johnson et al. (2025) showed that temperate macroalgae and mobile reef invertebrates are disproportionately represented among provisionally threatened species based on IUCN Red List criteria, yet are under-represented in formal assessments. Many of these species are endemic, implying high regional conservation responsibility (Johnson et al., 2025).

For the live-bearing sea star Parvulastra vivipara in Tasmania, historical and contemporary surveys reveal >90% declines in density, local extirpations at one-third of documented sites, and extremely small, isolated populations at others, justifying its listing as Critically Endangered (Strain et al., 2024). In a subarctic embayment in Newfoundland, soft-sediment macrofauna revisited after two decades showed altered community structure, with lower density but similar richness, and shifts from highly tolerant deposit-feeding polychaetes to a more even assemblage including more bivalves, linked to coarser sediments and higher organic matter (Komendić et al., 2024). In Swedish MPAs, deep-learning-assisted video analysis of benthic invertebrates over 26 years revealed community shifts toward smaller, heat-tolerant suspension feeders and depth migrations of large, heat-sensitive taxa, reinforcing temperature as a key driver of functional change (Nilsson et al., 2025).

These and other studies collectively point to pronounced, but taxon- and region-specific, changes in invertebrate communities under climate and anthropogenic pressures, often with little formal reflection in global threat listings.

Decadal-scale datasets reveal dramatic declines in temperate macroalgae-associated invertebrates and mobile reef taxa. Endemic species such as *Parvulastra vivipara* show >90% population declines, meeting criteria for Critically Endangered status. Long-term benthic surveys in Sweden and Canada show functional shifts in assemblages

driven by warming, altered sedimentation, and habitat change.

Coastal and Reef Habitat Assemblages

Island, lagoon and estuarine systems provide further insights. In Malamawi Island (Philippines), macroinvertebrate gleaning grounds support at least 64 species across four phyla, 70% of them edible, with seagrass beds hosting the highest richness; yet diversity indices indicate very low to moderate diversity, with anthropogenic disturbances likely driving poor assemblage condition (Sahidjan et al., 2025). In Setiu Wetlands (Malaysia), DNA barcoding of 98 COI sequences revealed 32 molecular operational taxonomic units (MOTUs), including cryptic diversity within morphospecies and effective rapid assessment of poorly known aquatic invertebrates (Ghazali et al., 2025). Along Brazilian coasts, macroalgae-associated invertebrates and sponge assemblages in marine lakes illustrate both high biodiversity and the importance of habitat-specific sampling for conservation baselines (Vicente et al., 2024; Maas et al., 2024).

Studies from the Philippines, Malaysia, and Brazil demonstrate high local diversity, cryptic lineages, and the importance of structured habitats such as seagrass beds, macroalgae, and lagoons. DNA barcoding and integrative taxonomy reveal under-estimated diversity and the value of molecular tools for rapid assessments.

Multiple Stressors Affecting Marine Invertebrates

Marine invertebrates are among the first receivers and integrators of chemical contamination in coastal environments. Within mussels, early life stages are particularly sensitive to endocrine disruptors. In *Mytilus coruscus*, environmentally realistic bisphenol A (BPA) exposures inhibit larval development and metamorphosis, disrupt muscle development, and alter gene expression related to muscle growth, autophagy, AMPK signalling and detoxification (Huang et al., 2025). Similarly, low doses of the herbicide ioxynil and synthetic estrogen diethylstilbestrol reduce heart rate, depress immune-related gene expression and impair shell growth, with neuroendocrine pathways implicated in cardiotoxicity (Li et al., 2023). Notably, some growth effects occur at lower doses than those eliciting strong transcriptomic responses, underlining the potential for subtle, chronic impacts that evade detection by conventional biomarkers.

Heavy metal bioaccumulation constitutes another pervasive threat. In the Karnafully estuary (Bangladesh), Pb, Cd, Cu and Cr accumulate in six mollusc species, with some tissue concentrations exceeding human health limits and clear seasonal and spatial patterns (Niloy et al., 2024). Risk assessments indicate low acute toxicity for most combinations, but elevated risk for particular taxa and sites, emphasizing the importance of species-specific and life-stage-specific monitoring (Niloy et al., 2024). Bryozoans in eastern Aegean ports and marinas similarly accumulate Pb, Cd, Cu, V and Zn, reflecting contamination from antifouling paints and urbanisation, with tolerant alien and cryptogenic species serving as effective biomonitors (Koçak & Küçüksezgin, 2025).

Emerging contaminants such as microplastics, nanoplastics and bioplastics add complexity. Reviews of environmental impact assessment methods for these materials highlight data gaps in fate, bioaccumulation and toxicity of bio-based plastics, and stress the need for organism-level and mesocosm bioassays, including marine invertebrate endpoints, within integrated risk frameworks (Ballesteros et al., 2025).

Marine invertebrates experience complex combinations of stressors rather than isolated pressures.

Table 2. Examples of stressors and responses in marine invertebrates

Stressor / interaction	Taxa / system	Response type	Key findings	Ref.
Chronic warming	Reef fishes vs invertebrates (Tasmania)	Community & abundance trends	Fishes track short-term temperature pulses; invertebrates show long-term declines with limited seasonal variability	Herrera Fuchs et al., 2025
Seawater warming & eutrophication	Seagrass meadows (Northern Adriatic Sea)	Habitat loss, drivers	30–89% reduction in *Cymodocea nodosa* cover linked to warming, nutrients, light and sediment changes	Gianni et al., 2025
BPA exposure	Mussel larvae *Mytilus coruscus*	Development, metamorphosis	Impaired larval metamorphosis, malformed muscle development, altered expression of muscle growth and detoxification genes	Huang et al., 2025
Diethylstilbestrol (DES) & ioxynil	Juvenile & adult *M. coruscus*	Cardiac performance & shell growth	Reduced heart rate, immune suppression, and reduced shell growth associated with neuroendocrine disruption	Li et al., 2023
Heavy metals (Pb, Cd, Cu, Cr)	Estuarine molluscs (Karnafully Estuary, Bangladesh)	Bioaccumulation & human health risk	Elevated tissue concentrations; species- and site-specific risks for human consumers	Niloy et al., 2024
Ship noise	Cultured mussels (*Mytilus galloprovincialis*)	Behaviour (valve closure)	Clear coupling between ship passages and valve closure events, indicating acute behavioural responses	Torres-Guijarro et al., 2025
Multiple stressors (e.g. temperature, pH, contaminants)	Marine bivalves (global)	Performance & survival	Antagonistic and additive responses dominate; ecological realism limited by adult- and lab-biased studies	Rynkowski et al., 2025
Mussel farming	Soft-bottom macroinvertebrates (Chile)	α- and β-diversity, community structure	Decreased local (α) diversity and increased β-diversity via species replacement and ecological drift near farms	Vásquez et al., 2025

Climate Change and Ocean Acidification

Climate change alters marine invertebrate communities via chronic warming, changing thermal variability, acidification and associated shifts in oxygen and productivity. Along Tasmania's east coast, fishes show dynamic seasonal responses to temperature but limited net long-term change, whereas mobile invertebrates exhibit limited seasonal variability yet substantial multi-decadal declines, suggesting that less mobile taxa are particularly vulnerable to cumulative thermal stress (Herrera Fuchs et al., 2025). At Australian reefs, decadal declines in macroalgae and mobile invertebrates align with warming trends and extreme events, highlighting the potential for unrecognized extinction risk among under-studied taxa (Johnson et al., 2025).

In the northern Adriatic Sea, seagrass meadows—critical habitats for many invertebrates—have declined markedly, with Cymodocea nodosa experiencing 30–89% reductions in cover between 2014 and 2018 (Gianni et al., 2025). Generalized additive models identify warming, changes in nutrients, light regimes and sediment type as key drivers of occurrence patterns, with local-scale stressors shaping resilience and recovery potential (Gianni et al., 2025). Such changes cascade to invertebrate assemblages via altered habitat structure, food availability and microclimates.

Ocean acidification (OA) directly alters acid–base balance, carbonate chemistry and neural physiology. In a cephalopod model, transcriptomic analyses of the central nervous system and eyes under elevated CO_2 reveal OA-induced changes in

neurotransmission, neuroplasticity, oxidative stress and immune pathways, with correlated behavioural shifts (Thomas et al., 2024). These results bridge subcellular responses and whole-animal behaviour, emphasizing that neural effects of OA could profoundly reshape predator–prey interactions and invertebrate community dynamics.

Warming, acidification, hypoxia, and circulation changes shift physiological thresholds, community composition, and habitat suitability. Invertebrates—often less mobile than fishes—exhibit strong long-term declines. OA studies link CO_2-induced neural and behavioural changes in cephalopods to altered neurotransmission and oxidative stress pathways.

Chemical Pollution and Endocrine Disruptors

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Mussels (*Mytilus coruscus*) exhibit disrupted metamorphosis, impaired cardiac function, and suppressed immune pathways in response to BPA, herbicides, and synthetic estrogens. Heavy metal bioaccumulation in estuarine molluscs from Bangladesh surpasses human safety thresholds, showing site-specific contamination risks.

Noise Pollution and Habitat Disturbance

Anthropogenic noise constitutes an increasingly recognized stressor. At a mussel cultivation raft, high-frequency non-invasive valvometry revealed clear cause-and-effect relationships between ship noise and valve closure events in Mytilus galloprovincialis, indicating acute behavioural responses that may compromise feeding and growth (Torres-Guijarro et al., 2025). Laboratory experiments further suggest that artificial sound can jeopardise symbiotic interactions between hermit crabs and anemones, pointing to subtle community-level consequences (Solé et al.,

2024). These studies underscore the need to incorporate soundscapes into invertebrate conservation, particularly in busy shipping lanes and port areas.

Aquaculture and farming can both support and threaten invertebrate biodiversity. Conservation aquaculture aims to aid species recovery, but simplified hatchery environments can generate maladaptive phenotypes. A review of phenotypic plasticity in marine organisms used for conservation aquaculture highlights altered behavioural and morphological traits in captivity and shows that introducing ecologically relevant stimuli can mitigate some effects, improving post-release survival (Latini et al., 2025). Conversely, intensive mussel farming can drive species replacement and increased β-diversity through neutral processes such as ecological drift and dispersal, particularly affecting small, low-dispersal endemic taxa around Chilean farms (Vásquez et al., 2025). Together, these findings emphasize that aquaculture, including restoration-focused programs, must be designed with explicit attention to community- and landscape-level consequences.

In shallow gleaning grounds, chronic extraction of edible macroinvertebrates without regulation appears to depress diversity; in Malamawi Island, poor assemblage condition and low diversity are more consistent with anthropogenic harvesting than with natural monsoonal variability (Sahidjan et al., 2025). Trade and handicraft production using marine wildlife, including invertebrates, further contributes to pressure on populations in some regions (Ruenes et al., 2024).

Noise from ship traffic triggers acute valve-closure responses in farmed mussels, reducing feeding efficiency. Experiments with hermit crab–anemone symbioses suggest that artificial sound alters ecological interactions. Aquaculture-driven species replacement and extraction pressures in gleaning grounds reduce diversity and alter assemblage structure.

Multi-Stressor Interactions

Real-world invertebrate populations experience interacting stressors rather than single pressures. A systematic review and meta-analysis of multiple stressors on marine bivalves demonstrates a prevalence of antagonistic and additive responses, with an overall antagonistic tendency (Rynkowski et al., 2025). Many studies focus on adult stages, climate-related global stressors and laboratory settings, revealing biases that limit ecological realism. The dominance of antagonism may partly reflect experimental design and stressor selection, underscoring the necessity for field-based, early-life-stage, and local-stressor-focused research (Rynkowski et al., 2025).

Weight-of-evidence (WOE) approaches offer a way to integrate chemical, toxicological and biological lines of evidence. In northern Adriatic Natura 2000 sites, a quantitative WOE model combining sediment chemistry, ecotoxicology and benthic community indices concluded that overall ecological risk was low to slight, with localized chemical hazards (As, Hg, PAHs) but undisturbed communities and absent bioassay toxicity (Piccardo et al., 2024). Such frameworks help distinguish between chemical contamination and biologically relevant risk, an important distinction when prioritizing management in multi-stressor settings.

Meta-analyses show that antagonistic interactions are more common than synergistic ones, indicating complex ecological dynamics. Weight-of-evidence (WOE) frameworks integrate chemical, biological, and ecological indicators to better characterize risk across stressors.

Advances in Molecular Tools and Holobiont Research

Cryptic Diversity and Species Delimitation

Genomic and barcoding approaches are transforming marine invertebrate systematics and conservation. Whole-genome molecular resolution has resolved a cryptic species within the intertidal snail Littoraria complex, demonstrating that L.

flammea north of the Yangtze River estuary is reproductively distinct from L. melanostoma, with strong genomic divergence and differentiating functional genes linked to reproduction and protein binding (Xu et al., 2024). Likewise, integrative analyses of the deadly box jellyfish Chironex yamaguchii show that populations in Japan and the Philippines are morphologically similar but genetically diverged, forming distinct clades and suggesting cryptic species and potential reproductive isolation (Boco et al., 2025).

DNA barcoding of aquatic invertebrates in Setiu Wetlands reveals high diversity, cryptic lineages and the importance of building regional barcode libraries to accelerate species identification and monitoring (Ghazali et al., 2025). In coastal lagoons, global syntheses of benthic foraminifera point to major gaps in species discovery and distribution, reinforcing the need for integrative taxonomy combining morphology, molecular markers and ecological data (Belart et al., 2025). At larger scales, sponge diversification in marine lakes reveals fine-scale population structure and micro-evolutionary dynamics that inform phylogeography and conservation of sessile invertebrates (Maas et al., 2024).

To support robust taxonomic assignments, interlaboratory studies assessing the use of GenBank for wildlife identification highlight strengths and pitfalls, emphasizing the value of curated reference databases, standardised protocols and transparent reporting for both conservation and regulatory applications (Patel et al., 2023).

Genomic analyses reveal cryptic species complexes in gastropods and jellyfish, resolving previously ambiguous taxonomy and biogeographic structure. DNA barcoding enhances detection of hidden diversity and accelerates species identification for monitoring and management.

Genomic Architecture and Evolutionary Potential

Beyond barcoding, high-quality genomes enable insights into structural variation, adaptation and evolutionary history. In abalones, haplotype-phased genome assemblies reveal large non-syntenic regions on several chromosome pairs, driven by segmental duplications enriched for adaptive gene domains (Hirase et al., 2026). These non-syntenic homologous chromosomes appear conserved across related species, suggesting that structural variation has played a key role in the evolutionary success and diversification of abalones (Hirase et al., 2026).

Such studies underscore that genetic and structural variation can influence resilience to environmental change, but also highlight how limited genomic resources still are for most marine invertebrates. Targeted genome projects for ecologically or economically important species, including those already showing vulnerability to climate or pollution, are likely to yield disproportionate conservation returns.

High-quality abalone genomes show structural variation and segmental duplications linked to adaptive traits, offering insights into evolutionary resilience and diversification.

Microbiomes, Phages, and Host Interactions

Marine invertebrates are not isolated individuals but holobionts composed of host plus symbiotic microbial communities. Reviews of viruses in marine invertebrate holobionts emphasize the diversity and functional importance of bacteriophages in sponges, corals and other hosts, including roles in initial bacterial colonisation, maintaining symbiosis and contributing to disease (Zhou et al., 2024). Phage-host dynamics may modulate holobiont resilience to environmental change, yet remain poorly understood.

At finer scales, microbiome studies reveal complex host–microbe interactions during development. In the perivitelline fluid

(PVF) of Kellet's whelk, a diverse bacterial community dominated by Roseobacter species displays functional gene repertoires linked to symbiosis, quorum sensing and antibiotic biosynthesis, suggesting roles in embryo defence and development (Daniels et al., 2024). For the biofouling tubeworm Hydroides elegans, bacterial envelope polysaccharides (O-antigens) from inductive Gram-negative biofilm bacteria, rather than lipid A, trigger larval settlement and metamorphosis, revealing a specific molecular cue underlying a key life-history transition (Freckelton et al., 2024). Such mechanistic insights connect microbiomes, life cycles and habitat colonisation processes.

Holobiont studies illuminate roles of bacteriophages in coral, sponge, and mollusc symbiosis. Microbial communities in egg masses and larval settlement processes influence development and habitat selection.

Cell Lines and Stem-Cell Technologies

Despite decades of effort, stable long-term cell cultures from marine invertebrates remain elusive. A critical appraisal of the field identifies four major knowledge gaps: optimizing culture media, extending stemness of isolated cells, leveraging omics to refine culture conditions, and selecting appropriate cell types for in vitro systems (Rinkevich & Pomponi, 2025). Addressing these will require coordinated, species-specific approaches and collaboration across laboratories and taxa.

Parallel developments in stem-cell technologies for wildlife conservation are beginning to encompass non-mammalian taxa, including marine species (Hutchinson et al., 2024). Reprogramming somatic cells, in vitro gametogenesis, and embryo modelling could ultimately support genetic rescue, assisted reproduction and disease modelling for threatened invertebrates. However, technical hurdles, ethical considerations and governance frameworks must be carefully developed before these tools can be widely deployed.

Although long-term marine invertebrate cell cultures remain challenging, targeted efforts in media optimization, stemness maintenance, and omics-based refinement show promise for conservation biotechnology, toxicology, and disease modelling.

Molecular Stress Physiology

Transcriptomic and molecular studies reveal the mechanistic underpinnings of stress responses. In cephalopods, OA-induced shifts in central nervous system gene expression involve neurotransmission, neuroplasticity, immune and oxidative stress pathways, with clear behavioural correlates (Thomas et al., 2024). Contaminant exposures in mussels alter expression of muscle growth genes, detoxification pathways, autophagy and neuroendocrine signalling (Huang et al., 2025; Li et al., 2023). In coral reef ecosystems, integrated eDNA and morphological approaches reveal heavy metal-associated (arsenic) shifts from stochastic to more deterministic community assembly processes in benthic invertebrates, linking chemical pollution to assembly theory (Zhang et al., 2025).

These molecular insights, when integrated with demographic and community-level data, can inform thresholds, early-warning indicators and mechanistic models of vulnerability and recovery. Transcriptomic work connects pollutant exposure, OA, and chemical stressors to pathways involving immune response, autophagy, neurotransmission, and metabolic regulation.

AI, Risk Assessment, and Spatial Conservation Planning

AI-Assisted Monitoring

The proliferation of high-volume image and video datasets from underwater observatories and surveys has spurred the adoption of AI for invertebrate monitoring. In a Swedish MPA, an object-detection model trained to recognise 17 benthic invertebrate taxa in video archives achieved high precision and generated >72,000

occurrence records from footage spanning 1997–2023, enabling analyses of depth distributions, abundance trends and functional composition over time (Nilsson et al., 2025). The study demonstrates that deep learning can (i) reconstruct multi-decadal trajectories for diverse taxa, (ii) reveal trait-based shifts (towards smaller, heat-tolerant suspension feeders) and (iii) inform management actions such as extending protection to deeper, cooler waters (Nilsson et al., 2025).

More broadly, AI applications in oceanographic data analysis—from pattern recognition in physical and chemical datasets to modelling ecological responses—offer powerful tools for predicting invertebrate distribution, tracking stress exposure and prioritising conservation interventions (Osei et al., 2025). However, their utility hinges on data representativeness, taxonomic accuracy and transparent model evaluation.

Deep-learning models accurately classify benthic invertebrates in long-term video datasets, producing large-scale occurrence records that enable temporal and functional analyses across decades.

Integrated Risk Assessment
WOE approaches combine chemical contamination, ecotoxicological testing, and community indices to distinguish between hazard presence and ecologically meaningful risk.

Geospatial Conservation Planning
Global reviews highlight gaps in representing invertebrates and deep-sea habitats in spatial planning. β-diversity analyses contribute to understanding connectivity and recovery processes relevant for MPA network design.

Governance, Welfare, and Sustainable Use
Taxonomic Capacity and Documentation
Limited local taxonomic expertise in biodiverse regions reduces capacity for conservation assessments. Long-term curated collections are crucial for distribution mapping, species discovery, and regulatory enforcement.

Invertebrate Welfare and Ethics
Recognition of invertebrate sentience and welfare is growing, prompting reconsideration of research, exploitation and management practices. A postscript on invertebrate welfare argues that human activities—from industrial fishing to pollution and climate change—are the primary drivers of invertebrate suffering and calls for integrating welfare considerations into conservation and policy (Winlow et al., 2024). This includes minimizing unnecessary harm in research, considering welfare in aquaculture and restoration programs, and acknowledging invertebrates in animal ethics frameworks.

Trade in invertebrates for zoohandicrafts and other cultural artefacts can have significant, yet often undocumented, impacts on local populations. Investigations of marine wildlife used in Brazilian handicrafts show expanding markets and potential sustainability concerns, emphasizing the need for regulation, monitoring, and alternative livelihood programs (Ruenes et al., 2024). Cultural representations of aquatic invertebrates in literature, such as ecopoetic explorations of local invertebrate encounters, can also play a role in shifting public perception and promoting empathy towards less charismatic taxa (Fibisan, 2024).

Growing evidence of invertebrate sentience calls for integration of welfare considerations into research, aquaculture, exploitation, and policy-making.

Blue Bioresources and Bioactive Metabolites
Marine invertebrates harbor rich biochemical diversity with applications in nutraceuticals, pharmaceuticals, and functional foods. Ensuring sustainable sourcing and ethical governance is essential to avoid overexploitation.

DISCUSSION

This literature review reveals that while marine invertebrates are fundamental to ecosystem function and human wellbeing, they are experiencing unprecedented pressures in the Anthropocene. Long-term monitoring data underscore the vulnerability of low-mobility taxa to climate warming and extreme events. The prevalence of antagonistic multi-stressor responses challenges traditional ecological prediction models, highlighting the need for more realistic experiments incorporating local stressors and early life stages.

Rapid advances in molecular biology—including genomics, barcoding, and holobiont studies—are transforming species delimitation, allowing detection of cryptic diversity and improved understanding of physiological responses. However, large gaps in taxonomic capacity and biogeographic documentation hinder comprehensive conservation planning.

AI-driven monitoring has begun to revolutionize ecological data processing, enabling near-automated, long-term, multi-taxon datasets that were previously impractical to analyze manually. Still, model accuracy and data representativeness remain challenges.

Governance frameworks must integrate biodiversity conservation with blue bioeconomy development, welfare considerations, and equitable access to resources. Without coordinated global and regional action, many invertebrate taxa may continue to decline unnoticed.

CONCLUSION

Marine invertebrates face accelerating threats, yet remain underrepresented in conservation research and policy. Integrating long-term ecological monitoring, molecular tools, AI, and socio-ecological frameworks is essential to improving conservation outcomes. Future initiatives must prioritize taxonomic capacity-building, holistic monitoring, ethical considerations, and sustainable use to secure the resilience of marine invertebrates in a rapidly changing world.

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