

Understanding Aquatic Pollutants: Identifying Challenges for Sustainability and Biodiversity

Christyn Bailey¹  | Helmut Segner² ¹John Wiley and Sons, Oxford, UK | ²Centre for Fish and Wildlife Health, Vetsuisse Faculty, University of Bern, Länggassstrasse 122, Bern 3012, Switzerland**Correspondence:** Christyn Bailey (chbailey@wiley.com)**Received:** 17 March 2026 | **Revised:** 17 March 2026 | **Accepted:** 19 March 2026

Aquatic ecosystems face increasing threats from a plethora of harmful environmental pollutants that pose major challenges to biodiversity. These pollutants—including but not limited to microplastics, heavy metals, pesticides, persistent organic pollutants and emerging contaminants—can have widespread impacts on aquatic life and overall ecosystem health [1, 2]. Global aquaculture intensification contributes to this problem in a feedback loop acting in the fashion of a circular causality: it generates harmful substances such as excess nutrients, particulate matter, fish waste, antibiotics and microplastics. At the same time, aquaculture is affected by these pollutants, which contaminate product safety, potentially affecting human health and negatively impacting sustainability and production [3–5].

As aquaculture continues to expand, it is increasingly important to understand both the local and global impacts of aquatic pollutants, including their sources, pathways and toxicological effects. The latter aspect includes not only direct pollutant effects on the cultured organisms but also on organisms influencing the aquatic milieu, such as bacteria or algae. This knowledge is essential for prioritising toxic hazards and for developing effective management strategies that support the long-term viability of aquaculture and the conservation of aquatic biodiversity. Despite existing management practices, policies and regulations aimed at reducing pollution from nutrients, waste, chemicals and plastics, significant improvements are still needed to achieve sustainable aquaculture.

Against this backdrop, the present thematic collection brings together contributions from *Aquaculture Research* that examine how diverse classes of aquatic pollutants intersect with aquaculture production, organism health and environmental sustainability. It highlights the dual relationship between aquaculture and pollution—both the pollutants generated by aquaculture and how aquaculture is affected by them—while considering strategies for

mitigation. The articles within the collection examine pollutant effects on aquatic life at molecular, cellular, physiological, ecological and ecosystem levels, as well as their implications for production and sustainability. Taken together, the studies illuminate the emerging challenges of a range of pollutants, reveal the complexity of multi-stressor interactions and point to approaches that can promote more sustainable aquaculture and better protect aquatic biodiversity. Overall, the collection underscores the urgent need for integrated strategies to reduce aquatic pollution while maintaining productive and safe aquaculture systems worldwide.

Among the dominant themes emerging from the collection, several manuscripts addressed the toxic effects of agrochemicals such as pesticides and insecticides, with a particular emphasis on tissue pathology and physiological disruption. These included a study evaluating the effects of chlorpyrifos, a widely used organophosphate pesticide and neurotoxin, on haematological and oxidative stress parameters in the silver barb (*Barbonymus gonionotus*), and a report on the modern insecticide Voliam Flexi, which demonstrated antioxidant suppression and tissue degeneration in juvenile African catfish (*Clarias gariepinus*) [6, 7]. A further study explored both acute and chronic exposure to cypermethrin, an insecticide in carp (*Cirrhinus mrigala*), revealing significant growth impairments, disruptions in key enzyme activities and reductions in essential biochemical nutrients [8]. In summary, these studies demonstrate that agrochemicals, particularly pesticides and insecticides, exert widespread physiological and tissue-level damage in aquatic species, highlighting both the severity of their impact and the need for effective mitigation strategies.

Beyond agrochemicals applied within or near production systems, several studies examined contaminants originating from broader environmental inputs to aquaculture operations, particularly heavy metals. Park et al. [9] investigated the effects of waterborne arsenic exposure on the starry flounder (*Platichthys stellatus*), a

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Copyright © 2026 Christyn Bailey and Helmut Segner. *Aquaculture Research* published by John Wiley & Sons Ltd.

contaminant widely detected in aquatic ecosystems and often associated with anthropogenic industrial activities. They reported significant reductions in haemoglobin levels, haematocrit and red blood cell counts, clearly demonstrating the adverse impacts of arsenic on haematological physiology [9]. Moreover, Appiah and colleagues examined mercury, cadmium and arsenic levels in water, sediment, finfish and shellfish from the Tano River in Ghana's Western North Region, demonstrating the bioaccumulation of toxic elements across environmental compartments and cultured organisms, and highlighting potential food safety risks linked to background contamination [10]. Adjei et al. [11] further showed how heavy metal contamination in water, sediment and fish from the Barekese Reservoir, also in Ghana, can disrupt ecosystem processes and pose risks to both aquatic biota and human consumers. Taken together, these studies highlight source-dependent risk pathways that originate largely outside farm boundaries, accentuating the need for catchment-scale monitoring and regulatory oversight to mitigate contaminant inputs that are often beyond the direct control of individual producers.

In contrast to background contamination, several studies focused on compounds that arise directly from aquaculture production activities, particularly the use of antibiotics and other pharmaceuticals, as well as nitrogenous waste products generated through intensive culture practices. These stressors are closely tied to farm-level decisions and therefore represent risk pathways that are, at least in part, amenable to management intervention. A prominent theme across several studies was the growing burden of pharmaceutical and antibiotic contamination, driven by the widespread and often unregulated use of veterinary drugs in aquaculture. Research featured here documented profound physiological and molecular disruptions associated with antibiotics such as oxytetracycline and florfenicol, as well as other emerging pharmaceutical contaminants. Reported effects included altered immune gene expression, neurotoxicity, tissue degeneration and disrupted metabolic function, demonstrating that even therapeutic use can carry unintended biological consequences [12–14].

Waga et al. [15] investigated both contaminant pathways mentioned above (those originating from broader environmental inputs to aquaculture systems and those exploring the role of compounds that arise directly from aquaculture production activities) by simultaneously assessing antimicrobial residues and heavy metals in aquaculture farms in Nairobi County, Kenya. While antibiotic concentrations were below established maximum residue limits—suggesting fish were safe for human consumption—the authors noted that chronic exposure to low concentrations may still contribute to antimicrobial resistance, cytotoxic effects and environmental pollution. At the same time, detected lead and chromium concentrations exceeded the European Commission maximum residue limit of 0.05 mg/kg for fish muscle, indicating overlapping risks from both production-derived inputs and background contamination [15]. Beyond pharmaceuticals, nitrogenous waste was also identified as a key production-related stressor. In addition, Shi et al. [16] evaluated ammonia nitrogen stress in juvenile cichlids (*Pseudotropheus zebra*), showing that elevated ammonia levels—while not synthetic pollutants—can function as potent chemical stressors that disrupt respiration, immune responses, antioxidant capacity and the fish microbiota. While Xu et al. [17] demonstrated that biological components of aquaculture systems can further modulate production-related impacts.

The authors showed that the presence of *Macrobrachium nipponense* in *Macrobrachium rosenbergii* culture systems altered phytoplankton composition and water chemistry, with consequences for nutrient cycling and community structure [17]. Taken together, the evidence indicates that production-derived risks in aquaculture centre on antibiotics as a key concern, alongside nitrogenous waste accumulation and biological system design, each independently influencing organism health and environmental conditions. In a One Health context, these pressures highlight how aquaculture links animal health, environmental quality and human health through shared exposure and resistance pathways, underscoring the need for coordinated antimicrobial stewardship and system-level management.

Alongside chemical contaminants traditionally associated with agriculture and aquaculture, another body of research presented here focused on microplastic pollution and engineered nanoparticles, contaminants that can enter aquaculture systems from the surrounding environment but may also be introduced to aquaculture practices themselves. Microplastics are now firmly established as a pervasive stressor in aquatic ecosystems, with a growing evidence base documenting their distribution, ingestion and potential impacts [18]. Contributions to this collection demonstrated that microplastics infiltrate aquaculture not only via environmental exposure but also directly through commercial fish feeds, creating an immediate and underappreciated pathway of contamination [19]. Field-based studies further revealed widespread ingestion across both freshwater and marine species, while hazard assessments pointed to potential implications for food safety and human consumers [20, 21].

Engineered nanoparticles represent a more recent and rapidly evolving concern. Although their environmental presence is less well characterised than microplastics, accumulating evidence suggests that nanoparticles can exert toxicological and physiological effects on aquatic organisms, raising important questions about their behaviour, bioavailability and long-term consequences within aquaculture systems [22]. In this collection, studies assessed this emerging challenge, examining how nanoparticles interact with aquatic species and exploring strategies to mitigate their effects. Common carp (*Cyprinus carpio*) exposed to green-synthesised zinc oxide nanoparticles showed significant biochemical and tissue-level disruptions, highlighting the inherent toxicity of these nanoparticles [23]. Nile tilapia (*Oreochromis niloticus*) exposed to zinc oxide nanoparticles experienced oxidative stress, immune suppression and DNA damage, which was alleviated by dietary supplementation with chia seeds (*Salvia hispanica*) [24]. Together, these findings highlight the importance of regulatory and monitoring approaches that reflect the distinctive physicochemical properties of nanoparticles, which govern their bioavailability, toxicity and interactions within aquaculture environments.

While many studies necessarily examine individual pollutants in isolation, real-world aquaculture systems are shaped by simultaneous exposure to multiple stressors. For instance, Said et al. [25] investigated an often neglected but important aspect of environmental impacts, the issue of multiple stressors. In aquatic habitats as well as aquaculture systems, animals will rarely be exposed to a single stressor alone, but in most cases, there will be combinations of multiple overlapping pressures, be they from culture operations such as handling, or from pathogens, or from water quality

parameters and pollutants [26, 27]. Said et al. [25] assessed the combined effects of microplastics and the phenolic compound pyrogallol on red swamp crayfish. Their findings showed that co-exposure disrupted immune function, induced oxidative stress, and caused hepatopancreatic tissue damage, highlighting the compounded risks posed by concurrent chemical stressors. Notably, the multiple stressor exposure produced significantly greater biological disruption than either stressor alone, illustrating that microplastics often interact with other pollutants and that multi-stressor conditions can lead to more severe effects than single-stressor exposure [25]. In this context, it should be emphasised that while organisms may have evolutionary adaptations to changes in natural parameters such as temperature, anthropogenic stressors are emerging at an unprecedented pace and exhibit wide fluctuations in duration, intensity and geographic distribution, leaving many aquatic species insufficient time to adapt to their impacts. The issue is particularly pressing as simultaneous exposure to several anthropogenic stressors can produce nonlinear responses and unexpected physiological and ecological consequences, especially for immune function. Gaining a deeper understanding of how multiple stressors interact is therefore essential for anticipating complex ecological outcomes and for designing interventions that strengthen the resilience of aquaculture systems as well as aquatic ecosystems.

Importantly, the collection also moves beyond impact assessment to consider practical strategies for mitigating pollutant-related stress. In this context, in addition to identifying contaminant sources and impacts, a couple of studies explored approaches to protect cultured species and mitigate the negative effects of pollutant exposure, with particular emphasis on dietary interventions. Hassan et al. [28] investigated vitamin C supplementation as a mitigation strategy in silver carp (*Hypophthalmichthys molitrix*) fingerlings exposed to the insecticides temephos and buprofezin, reporting enhanced antioxidant capacity and improved physiological resilience under chemical stress. Similarly, authors studying African catfish exposed to bisphenol A explored plant-based feed interventions, showing that dietary supplementation with parsley (*Petroselinum crispum*) nanoparticles alleviated pollutant-induced disruptions in biochemical, hormonal and physiological biomarkers [29]. Examined in parallel, these findings demonstrate the potential of feed-based interventions—particularly plant-derived additives and essential nutrients—as environmentally friendly tools to enhance fish resilience, reduce pollutant-induced damage and support safer and more sustainable aquaculture practices in increasingly contaminated aquatic environments.

1 | Conclusion and Future Directions

Drawing on research conducted across diverse species and global contexts, this thematic collection demonstrates a clear unifying message: aquatic pollution is multifaceted, interactive and closely intertwined with the sustainability of aquaculture and the conservation of aquatic biodiversity. The studies highlight the need for integrated monitoring, improved chemical input management, and innovative mitigation strategies that account for both single-pollutant and combined effects.

At the same time, these converging lines of evidence indicate important areas where further research is needed. Notably, several reports focused on short-term, high-concentration exposures and

examined rapid response endpoints such as haematological and biochemical parameters. Such approaches provide a valuable foundation, particularly for species, regions, and contaminants where baseline knowledge remains limited. While a contrasting approach would be to employ longer-term, sublethal exposure scenarios that more closely reflect real-world conditions in many aquatic systems. Using similar assessments (i.e., immunological responses, tissue pathology and physiological impairment, etc.); however, in these scenarios the exposures may not cause immediate mortality but can substantially reduce an organism's capacity to cope with additional stressors, including pathogens. For these more chronic exposure scenarios, previous studies have investigated pollutant-induced changes to the microbiome, recognising its emerging role in host health, disease resistance and resilience under environmental stress [30]. In aggregate, these approaches point to the need for future work that integrates acute and chronic exposure frameworks, expands the use of functional and ecological endpoints, and places greater emphasis on host-microbiome interactions.

As aquaculture continues to expand to meet growing global food demands, effectively managing aquatic pollutants will be essential not only for ecosystem health and production resilience but also for safeguarding food security and public health. While the research brought together here primarily advances scientific understanding, the translation of these insights into policy development and governance—although not a core focus here—remains critical for long-term success. Strengthening links between experimental research, risk assessment and regulatory frameworks will be key to supporting sustainable aquaculture and the responsible stewardship of aquatic resources. By bringing together experimental, field-based and mitigation-focused studies, the work presented here provides a timely foundation for advancing more integrated, evidence-based approaches to managing aquatic pollution in aquaculture systems.

Author Contributions

Christyn Bailey and Helmut Segner: conceptualisation, writing – original draft, writing – review and editing.

Acknowledgments

We gratefully acknowledge all authors, reviewers, and editors who contributed to this thematic collection. Their expertise and commitment were instrumental in maintaining the scientific quality and coherence of the articles presented. We used Microsoft Copilot to assist with grammar, readability and style. All content and conclusions are my own and have been carefully verified for accuracy. We disclose this use transparently, as we believe that AI, when applied responsibly, can be a useful ally in scholarly communication.

Funding

No funding was received for this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article, as no datasets were generated or analysed during the current study.

References

1. D. Pal, R. Prabhakar, V. B. Barua, et al., "Microplastics in Aquatic Systems: A Comprehensive Review of Its Distribution, Environmental Interactions, and Health Risks," *Environmental Science and Pollution Research* 32, no. 1 (2025): 56–88.
2. W. Wu, R. Du, Z. Chen, W. Li, X. Huang, and Z. Pan, "Unlocking the Combined Impact of Microplastics and Emerging Contaminants on Fish: A Review and Meta-Analysis," *Aquatic Toxicology* 278 (2025): 107176.
3. O. H. Fred-Ahmadu, F. O. Ahmadu, A. E. Adedapo, I. Oghenovo, O. T. Ogunmodede, and N. U. Benson, "Microplastics and Chemical Contamination in Aquaculture Ecosystems: The Role of Climate Change and Implications for Food Safety—A Review," *Environmental Sciences Europe* 36, no. 1 (2024): 181.
4. X. Liu, Y. Wang, H. Liu, et al., "A Systematic Review on Aquaculture Wastewater: Pollutants, Impacts, and Treatment Technology," *Environmental Research* 262 (2024): 119793.
5. N. Kathijotes, L. Alam, and A. Kontou, "Aquaculture, Coastal Pollution and the Environment," in *Aquaculture Ecosystems: Adaptability and Sustainability*, eds. S. Mustafa and R. Shapawi, (Wiley, 2015): 139–163.
6. Z. Hossain, R. Akter, M. B. Moin, et al., "Evaluation of Chlorpyrifos as an Organophosphate Pesticide on Hematology, Blood Biochemistry, Antioxidant Capacity, Oxidative Stress, and Histopathological Changes in Juvenile Silver Barb (*Barbonymus gonionotus*)," *Aquaculture Research* 2025 (2025): 7426390.
7. M. Hamed, H. S. Abdel-Tawab, M. A. Abdel-Maksoud, A. Malik, S. Fatima, and C. J. Martyniuk, "Impacts of Voliam Flexi on Antioxidant Responses, Oxidative Stress, and Histopathological Changes in Juvenile African Catfish (*Clarias gariepinus*)," *Aquaculture Research* 2025 (2025): 8608065.
8. P. Kundu, S. Ray, A. K. Ghosh, et al., "Chronic and Acute Toxicity Effects of Cypermethrin on Growth, Enzyme Activity, and Biochemical Nutrients in Carp Fish (*Cirrhinus mrigala*)," *Aquaculture Research* 2026 (2026): 5431762.
9. S.-W. Park, B. Gong, M.-S. Heo, and J.-H. Kim, "Effects of Lethal Concentration 50, Hematological Parameters, and Plasma Components of Starry Flounder (*Platichthys stellatus*) by Waterborne Acute Arsenic (As^{3+}) Exposure," *Aquaculture Research* 2025 (2025): 6147078.
10. H. K. Appiah, I. O. Kusi, K. A. Obirikorang, S. Gyamfi, D. Adjei-Boateng, and R. E. Edziyie, "Bioaccumulation of Heavy Metals in Finfish and Shellfish Samples From Tano River, Ghana: A Food Safety Issue," *Aquaculture Research* 2026 (2026): 8285249.
11. P. Adjei, I. O. Kusi, K. A. Obirikorang, R. Edziyie, D. Adjei-Boateng, and P. Frimpong, "Heavy Metals in Raw and Treated Water, Sediment, and Fish at the Barekese Reservoir Headworks," *Aquaculture Research* 2025 (2025): 7649064.
12. C. Öntaş Kurtboğan, E. Baba, and M. D. Demircan, "The Effect of Oxytetracycline on the Immune Response and Expression of Immune-Related Genes in European Sea Bass (*Dicentrarchus labrax*, L. 1758)," *Aquaculture Research* 2025 (2025): 5777442.
13. F. Borjian Boroujeni, D. Shahsavani, M. Sarkheil, and H. Nourani, "Effects of Dietary Cerium Oxide Nanoparticles on Growth Performance, Plasma Biochemistry, and Histopathological Changes of *Cyprinus carpio* Koi Fish Exposed to Florfenicol Antibiotic," *Aquaculture Research* 2025 (2025): 9117730.
14. A. E.-D. H. Sayed, M. Hamed, R. F. Fathy, et al., "Ecotoxicological of Emerging Pharmaceuticals on African Catfish (*Clarias gariepinus*): Biomarkers for Neurotoxicity, Immunotoxicity, and Histopathology," *Aquaculture Research* 2025 (2025): 8868758.
15. E. M. Waga, G. O. Aboge, N. Gitahi, C. Heffernan, J. G. Nderitu, and L. Benton, "Antimicrobial Residues and Heavy Metals in Aquaculture Farms Within Nairobi County, Kenya," *Aquaculture Research* 2025 (2025): 9275802.
16. H. Shi, R. Sun, B. Wang, Y. Cui, and C. Zhang, "Ammonia Nitrogen Stress Disrupts Respiratory and Immune System, Antioxidant Capacity, and Intestinal Microbiota in Juvenile Cichlid Pseudotropheus Zebra," *Aquaculture Research* 2025 (2025): 3778308.
17. Y. Xu, Y. Feng, S. Zhang, et al., "Effects of *Macrobrachium nipponense* on Phytoplankton Communities and Water Environmental Factors in *Macrobrachium rosenbergii* Culture," *Aquaculture Research* 2024 (2024): 4218312.
18. C. Mossotto, A. Maganza, A. Gabetti, et al., "Tackling Micro(Nano) Plastic Pollution in Aquaculture Systems," *Current Opinion in Chemical Engineering* 48 (2025): 101104.
19. S. A. A. Nyem, M. K. Saifullah, I. Jahan, et al., "Microplastics in Commercial Fish Feed in Bangladesh: An Emergent Risk Factor for Aquaculture," *Aquaculture Research* 2025 (2025): 5591001.
20. M. T. Mondal, M. A. Khan, and M. G. Mortuza, "Microplastic Pollution in Indigenous Fish From the Padma River, Bangladesh: A Case Study," *Aquaculture Research* 2025 (2025): 9917204.
21. S. Hacısalıhoğlu, "A Hazard Index of Microplastics Contamination in Commercial Marine Fish Species and Mussels in the Southern Marmara Sea, Turkey," *Aquaculture Research* 2025 (2025): 6690338.
22. S. Singh, S. M. Prasad, and G. Bashri, "Fate and Toxicity of Nanoparticles in Aquatic Systems," *Acta Geochimica* 42, no. 1 (2023): 63–76.
23. H. Asad, T. Ahmed, H. Naz, et al., "Impact of Green-Synthesized Zinc Oxide Nanoparticles (ZnO NPs) on the Biochemical and Histological Profiles of *Cyprinus carpio*," *Aquaculture Research* 2025 (2025): 5327177.
24. H. M. Elsheshtawy, H. Elabd, H. H. Mahboub, et al., "Ameliorative Effects of *Salvia hispanica* Seeds Against Zinc Oxide Nanoparticles Toxicity Inducing Hemato-Biochemical Variables, Immune-Oxidative Stress, and DNA Damage in *Oreochromis niloticus*," *Aquaculture Research* 2025 (2025): 9922700.
25. R. E. M. Said, M. Hamed, W. M. Shaalan, H. A. M. Elbaghdady, and A. E.-D. H. Sayed, "Exploring the Coexposure Effects of Pyrogallol and Microplastic on the Red Swamp Crayfish *Procambarus clarkii*," *Aquaculture Research* 2025 (2025): 6084150.
26. H. Segner, M. Schmitt-Jansen, and S. Sabater, "Assessing the Impact of Multiple Stressors on Aquatic Biota: The Receptor's Side Matters," *Environmental Science & Technology* 48, no. 14 (2014): 7690–7696.
27. J. A. Orr, R. D. Vinebrooke, M. C. Jackson, et al., "Towards a Unified Study of Multiple Stressors: Divisions and Common Goals Across Research Disciplines," *Proceedings of the Royal Society B: Biological Sciences* 287, no. 1926 (2020): 20200421.
28. S. Hassan, I. Z. Qureshi, M. O. Alotaibi, et al., "Vitamin C Alleviates Oxidative Stress in Silver Carp (*Hypophthalmichthys molitrix*) Fingerlings Exposed to Toxicity Induced by Temephos and Buprofezin," *Aquaculture Research* 2026 (2026): 5747529.
29. Z. Hassan, R. M. Amen, H. Elabd, et al., "Dietary Protective Influence of *Petroselinum crispum* Nanoparticles on Some Biochemical, Reproductive Hormones, and Physiological Biomarkers of Female *Clarias gariepinus* (Burchell, 1822) Exposed to Bisphenol A Toxicity," *Aquaculture Research* 2025 (2025): 2121122.
30. R. Xavier, R. Severino, and S. M. Silva, "Signatures of Dysbiosis in Fish Microbiomes in the Context of Aquaculture," *Reviews in Aquaculture* 16, no. 2 (2024): 706–731.