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The Role of Molluscs in Monitoring Marine Pollution and its Connection to Climate Change and ESG

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Abstract

Molluscs possess a unique capability to filter and remove pollutants from water, offering a natural and effective solution to combat marine pollution. Their filtration process not only enhances water quality but also mitigates the detrimental impacts of contaminants on marine ecosystems. As climate change introduces unprecedented challenges, the resilience of molluscs—particularly in adapting to rising temperatures and ocean acidification—highlights their critical role in sustaining marine ecosystem balance. This paper reviews the literature on molluscs from 1874 to 2024, as documented in the Scopus database, analyzing 5,757

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publications retrieved on 8 March 2024. Five major insights emerged: (a) molluscs' significant ecological role, (b) the potential of marine bivalves for ecosystem health and sustainability, (c) the importance of monitoring molluscs to address climate change, (d) the scarcity of studies linking molluscs to Environmental, Social, and Governance (ESG) practices, and (e) existing knowledge gaps. Understanding and monitoring mollusc populations are essential for advancing environmental stewardship, fostering social responsibility, and promoting sound governance. Integrating these aspects within business operations can support marine ecosystem resilience and reflect a commitment to the planet's and society's holistic well-being.

Introduction

Due to their widespread occurrence, ecological diversity, and ability to bioaccumulate pollutants, molluscs are often used as bioindicators of marine pollution. As bioindicators, molluscs can signal the state of environmental health and the presence of contaminants. The advantages of using molluscs include their sedentary nature, which makes them representative of local conditions; their ability to accumulate and reflect levels of pollutants such as heavy metals, organic contaminants, and radionuclides in their tissues; and their often long lifespan, which allows for the monitoring of environmental changes over time.[1-2] Researchers analyze the concentration of pollutants in the tissue of molluscs to gain insights into the level of contamination in their environment. Some commonly used molluscs include mussels, clams, and oysters. They help identify early environmental stress signals before severe ecosystem impacts occur. Additionally, their reaction to pollutants offers insights into potential ecosystem risks and human health concerns related to consuming contaminated seafood, as noted by Yu.[3] The study of molluscs as bioindicators can involve various approaches, such as monitoring the bioaccumulation of substances over time, assessing the physiological responses (such as enzyme activity), or observing the changes in population dynamics and community structure related to pollution levels. Through these methods, molluscs contribute valuable data for assessing and managing marine environments.[2]

Molluscs are gaining increasing attention for their potential role in mitigating marine pollution and their connection to climate change and Environmental, Social, and Governance (ESG) practices. Studies have shown that molluscs can filter and remove pollutants from the water, effectively improving water quality and reducing the negative impacts of pollution on marine ecosystems.[5-6] This is particularly significant in the face of climate change, as rising temperatures and ocean acidification pose serious threats to marine biodiversity and ecosystem health. Molluscs have shown resilience to these changing environmental conditions and can play a vital role in maintaining the balance of marine ecosystems. Additionally, the connection between molluscs and ESG practices highlights the importance of incorporating sustainable and responsible management approaches to protect marine environments. By harnessing the natural filtration capabilities of molluscs and integrating them into coastal management strategies, we can mitigate marine pollution and contribute to our marine ecosystems' overall resilience and sustainability.[6-45] This paper aims to review the available literature on 'Molluscs' from 1874 to 2024 using the Scopus database and discuss the major insights from the review.

Materials and Methods

Figure 1 shows the overall flow of literature review processes employed in the present review study. On March 8, 2024, a search for 'Molluscs' in the Scopus database identified 5767 highly relevant papers. Bibliometric analysis, a recognized method for assessing research literature, is particularly valuable in scientific fields that benefit from computational data analysis and has seen a rise in scholarly publications.[46] VOSviewer, a software tool that creates clear graphical representations of bibliometric maps, is especially effective for large datasets.[47] To highlight trends in 'Molluscs' research from 1874 to 2024, we conducted a bibliometric

analysis using VOSviewer, which stands for visualization of similarities (www.vosviewer.com).

Scopus contains numerous important research papers and provides integrated analysis tools for generating informative visual representations.[48] VOSviewer was used to analyze each keyword, determining links, total link strengths, and co-occurrences with other keywords.

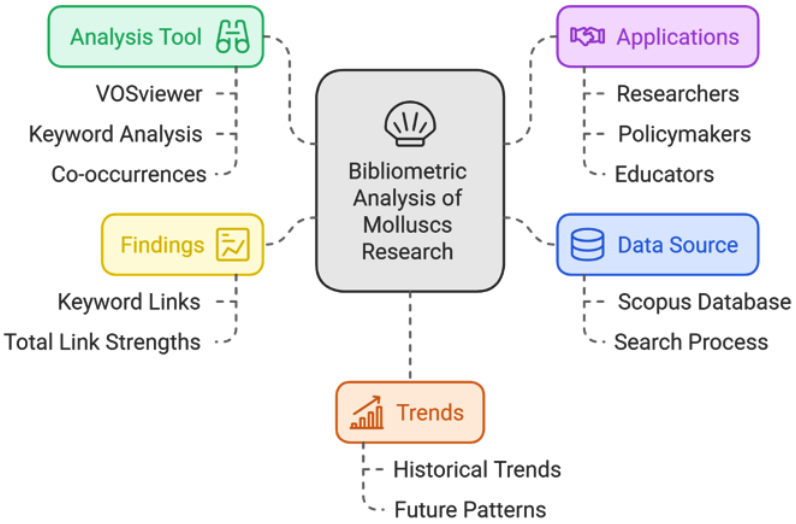

Fig.1: Overall flow of literature review processes employed in the present review study.

Results

Figure 2 provides a comprehensive overview of previous research, highlighting the co-occurrences of keywords related to 'Molluscs'. In this country networking map, it is observed that five main clusters of countries are involved in molluscs research. A distinct colour represents each cluster, and the number of countries within each cluster reflects the extent of collaborative efforts in different regions. Here is a breakdown of each cluster with the number of countries included

Cluster 1
(United States-Centered Cluster, Purple)

This central cluster, with 11 countries, includes the United States as the primary hub. Strong collaborations extend to countries like Canada, South Korea, Australia, and the United Kingdom. This cluster highlights the extensive partnerships led by the United States across continents.

Cluster 2 (European Cluster, Red)

This cluster includes 16 countries, including Germany, Italy, the Netherlands, Poland, and Switzerland. These countries are well-connected within Europe and maintain collaborative links with other continents, particularly with the United States, illustrating Europe's active role in mollusc research.

Cluster 3
(Russian Federation-Centered Cluster, Blue)

The Russian Federation anchors this cluster of nine countries, which includes Eastern European nations like Ukraine, Estonia, and Lithuania. This cluster demonstrates a regional research focus, with collaborations primarily within Eastern Europe and some connections with Asia.

Cluster 4
(Asian Cluster, Green)

This cluster comprises 13 countries and includes China, India, Japan, Malaysia, and Thailand. It reflects a growing research community within Asia, with substantial inter-Asian collaborations and links with the United States and European nations.

Cluster 5
(Franco-Mediterranean Cluster, Light Blue/Cyan)
This cluster, which includes 8 countries, is centred around France and includes Mediterranean countries like Spain, Algeria, Tunisia, and Morocco. France plays a central role in fostering collaborations within the Mediterranean region and with other European countries.

The map depicts 57 countries actively collaborating in mollusc research, illustrating the global nature of research in this field. The clustering of these countries underscores the strong regional ties within Europe, Asia, and the Mediterranean while also highlighting the central role of the United States in fostering cross-continental collaborations. This interconnected network shows how mollusc research benefits from extensive international partnerships, contributing to the global advancement of knowledge in this field.

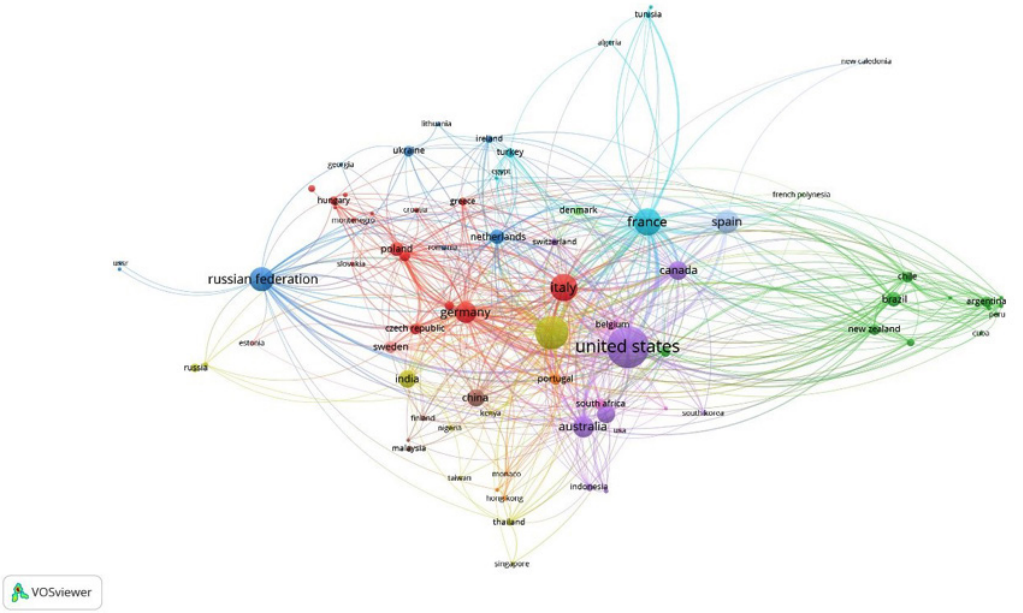

Fig. 2: A bibliometric analysis of 'Molluscs' research themes by country. This visualization shows the top 57 countries involved in research from 1874 to 2024, based on the Scopus database.

The analysis identifies five prominent clusters, as visualized in Figure 3 (top). Recent studies from 2010 to 2024 have concentrated on biodiversity, ecosystems, shells, marine environments, bioindicators, community composition, and morphology (Figure 3; bottom). This temporal dimension adds depth to the clusters identified earlier, offering insights into how the focus of research on molluscs and related fields has evolved over time.

Cluster 1 (Red)
focused on *mollusca, bivalvia*, and *gastropoda*, primarily includes keywords linked to taxonomic and biodiversity studies. The colors indicate that much of this foundational research began in the 1990s and continued into the early 2000s, showing a sustained interest in species classification, biodiversity, and morphological studies.

Cluster 2 (Green)
associated with environmental and chemical research, shows keywords such as *bioaccumulation, heavy metals*, and *water pollutants*. The greenish hues suggest that the investigation into bioaccumulation and ecotoxicology grew more prominent from the late 1990s into the 2000s, reflecting an increasing concern for environmental monitoring and pollution impact on marine species.

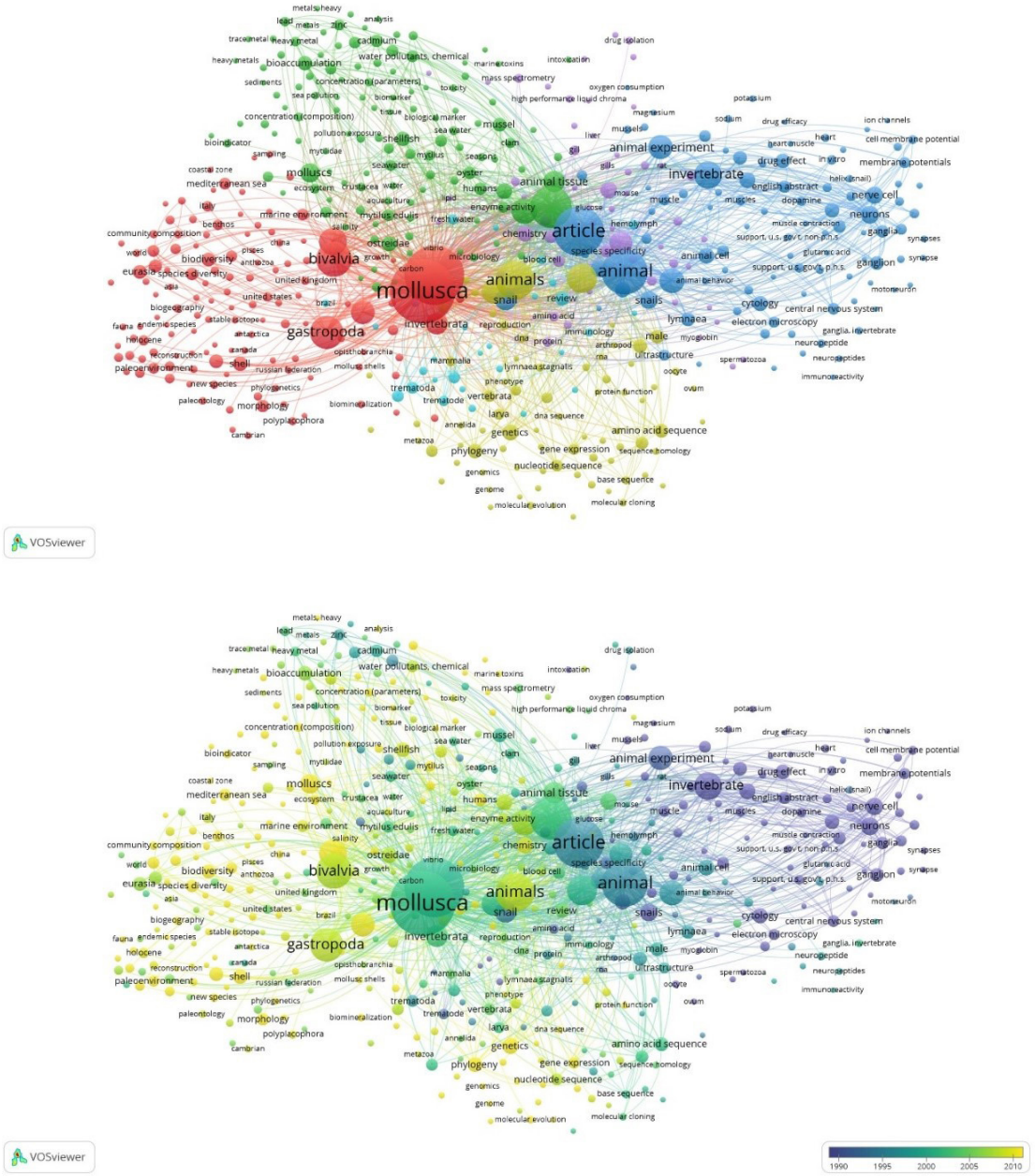

Fig. 3: A bibliometric analysis of 'Molluscs' research themes. The top panel visualizes the main research themes, while the bottom panel shows the evolution of research trends from 1874 to 2024, based on the Scopus database. The colors in the top panel represent different research themes, and the colors in the bottom panel indicate the publication years. Data is based on a Scopus search conducted on March 8, 2024.

Cluster 3 (Blue)
encompasses neurobiology and physiology topics, represented by terms like *nervous system*, *neurons*, and *dopamine*. The darker blue shades reveal that studies in this area have been consistently active from the mid-1990s onward, with research into

molluscan neurobiology and physiology gaining traction as laboratory techniques advanced.

Cluster 4 (Yellow)
representing genetics and molecular biology, contains terms such as *gene expression* and *nucleotide sequence*. The yellow hues suggest that genetic and molecular research became prominent in the early 2000s, corresponding with advancements in genomics and molecular techniques that allowed for deeper investigation into the genetic underpinnings of invertebrate species.

Cluster 5 (Purple)
focuses on experimental methodologies and pharmacology, with keywords such as *drug efficacy* and *toxicity.* The purple tones indicate that these topics gained popularity in the early to mid-2000s, highlighting the rise in laboratory-based experimental research and drug testing on molluscan models.

This map's temporal information allows for an understanding of how research themes have shifted over the years. As new technologies and methodologies emerged, it showed a trajectory from foundational taxonomy and biodiversity studies towards more specialized areas like neurobiology, ecotoxicology, and molecular biology. This temporal mapping of keywords helps illustrate the evolving focus in molluscan research and related fields.

Figure 4. shows the radar chart based on the top 110 countries out of 132 defined countries based on the Scopus database using the keyword 'Molluscs' from 1874 to 2024, with a total number of publications of 5757 as searched on 8 March 2024. The chart visually represents each country's contribution to the body of research on molluscs, with the number of papers indicated by radial points on the chart.

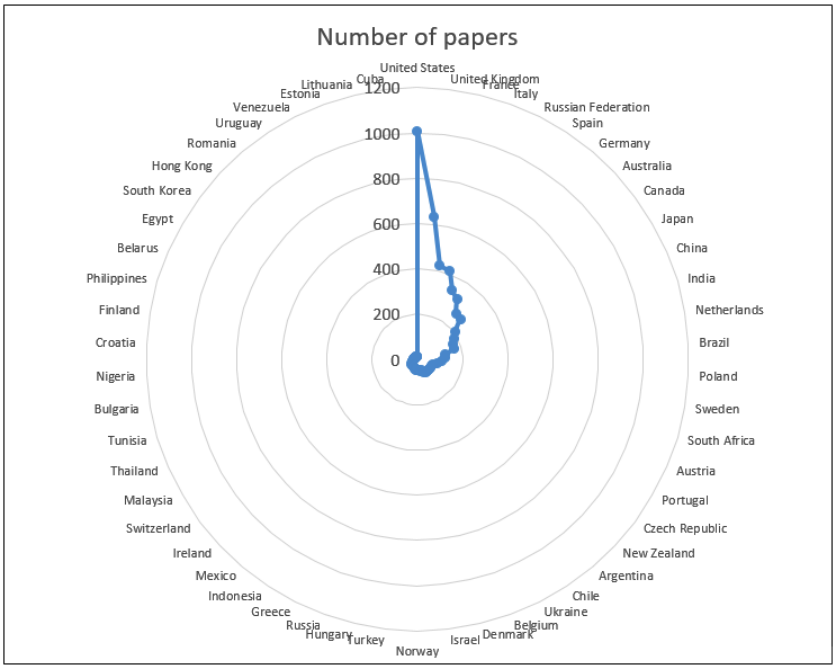

Fig. 4: Radar chart (using Excel) based on top 110 countries out of 132 defined countries based on Scopus database using keyword 'Molluscs' from 1874 to 2024, with a total number of publications of 5757 as searched on 8 March 2024.

The United States is the most prominent contributor, with the highest number of publications, exceeding 1,200 papers. This highlights the country's strong academic and research interest in mollusc studies. United Kingdom, Italy, Russian Federation, and Germany follow as significant contributors, each

with substantial publication counts ranging from 400 to 1,000 papers. These countries also play a central role in global mollusc research, reinforcing their positions as leaders in this field.

Other notable contributors include Spain, Australia, Canada, Japan, China, and India, each with a moderate number of publications between 200 and 400 papers. These countries represent a diverse range of geographic regions, indicating global interest in mollusc research.

Secondary contributors such as the Netherlands, Brazil, Poland, Sweden, South Africa, Austria, and Portugal show fewer but still noteworthy publication counts, indicating an active, though smaller, engagement in mollusc-related studies.

Countries with lower publication counts include Thailand, Malaysia, Switzerland, Tunisia, Croatia, and others, each contributing fewer than 100 papers. These nations may represent emerging research interests or smaller-scale studies in mollusk-related fields.

Discussion

The reported studies highlighted the significant role of molluscs

Research on molluscs increasingly highlights their vital role in mitigating marine pollution and addressing climate change impacts. Understanding the mechanisms through which molluscs contribute to ecosystem health is essential for fully utilizing their potential. Studies show that molluscs effectively filter and remove water pollutants, enhancing water quality and mitigating contaminants' impact on marine life. Their resilience to rising temperatures and ocean acidification highlights their crucial role in maintaining marine ecosystem balance.[8-10]

Restorative aquaculture has emerged as a promising approach to enhance ecosystem services and benefit society. By utilizing the natural filtration abilities of molluscs, this practice can help mitigate the local effects of ocean acidification, improve water quality and clarity, provide habitats for fish, increase benthic community diversity, support food security and job creation, and promote gender equity. This approach offers a holistic strategy, leveraging the unique capabilities of molluscs to create a healthier and more sustainable ocean environment.[11-12]

Given the alarming pace of global climate change and its severe threat to the diversity of marine bivalves, continued research and collaboration in this field are essential. By further exploring the potential of molluscs and developing comprehensive strategies, we can effectively address marine pollution and contribute to the resilience and sustainability of marine ecosystems worldwide.

The literature indicated the Potential of Marine Bivalves for Ecosystem Health and Sustainability

Accurate weather predictions are increasingly essential in our rapidly changing world, supporting critical sectors such as agriculture, transportation, energy production, and disaster management, which rely on reliable forecasts for effective planning and operations. Restorative aquaculture, which involves marine bivalves like molluscs, offers significant potential for enhancing ecosystem health and sustainability. By utilizing the natural filtering abilities of bivalves to improve water quality, remove pollutants, and mitigate ocean acidification, restorative aquaculture can create habitats for fish and other organisms, boost biodiversity, and deliver societal benefits such as food security and job creation.[49]

This holistic approach to aquaculture addresses complex environmental challenges by harnessing the biological traits of marine bivalves to restore ecosystem services while also considering socio-economic factors. Restorative aquaculture thus represents a promising pathway to sustainable development and the protection of marine ecosystems.[2,13-14]

Marine bivalves, particularly molluscs, play a pivotal role in restorative aquaculture. This approach supports ecosystem health through water filtration, ocean acidification mitigation, and biodiversity enhancement. Additionally, it provides numerous societal benefits, including improved food security, employment opportunities, and gender equity.[15-16]

As we confront the intertwined challenges of climate change and marine pollution, recognizing the interconnectedness of ESG factors is crucial for effective solutions. Research and collaboration are vital to understanding how marine bivalves support ecosystem health, enabling the development of strategies to maximize their potential.

Embracing restorative aquaculture and integrating marine bivalves into coastal management strategies is a proactive approach to fostering marine ecosystem resilience and sustainability. This commitment marks a significant step toward achieving sustainable development and ensuring the health of our oceans for future generations.[50]

Lacking of Studies on the Connections between Molluscs and ESG Practices

Integrating molluscs into ESG practices highlights the essential role of sustainable and responsible marine management. By incorporating molluscs into coastal strategies, organizations can address critical issues like marine pollution while enhancing the resilience and sustainability of marine ecosystems, illustrating the interconnectedness of ESG factors in tackling complex environmental challenges.[6-7,17-18]

To maximize molluscs' benefits in reducing marine pollution and countering climate change, it is crucial to delve into the specific mechanisms through which these organisms contribute to ecosystem health. Collaborative research in this area is vital for developing strategies that leverage molluscs' unique capabilities, fostering a healthier and more sustainable ocean environment. With climate change accelerating at an alarming rate, posing significant threats to marine biodiversity, this research is more urgent than ever.[19-20]

Restorative aquaculture, particularly through the cultivation of molluscs, presents substantial potential to enhance ecosystem services and benefit society. This approach can locally mitigate ocean acidification, improve water quality, provide habitats for fish, increase benthic community diversity, support food security, generate employment opportunities, and promote gender equity.[21-24] Including molluscs in these efforts can strengthen the long-term sustainability of marine ecosystems and the communities that rely on them.

Furthermore, integrating molluscs into ESG practices reinforces the need for sustainable, responsible approaches to marine management. Their role in coastal strategies helps reduce marine pollution and fortifies marine ecosystems' resilience. This approach underscores the importance of acknowledging the interconnectedness of environmental, social, and governance factors in overcoming complex environmental challenges.[25-27]

ESG considerations are increasingly critical for businesses demonstrating their commitment to sustainability and responsible practices.[28] A key aspect of this commitment involves monitoring marine ecosystems to gain insights into the environmental impact of corporate activities. Molluscs have emerged as valuable bioindicators, reflecting the effectiveness of marine biodiversity's health and pollution control efforts. By using molluscs in monitoring and restoration initiatives, companies can showcase their dedication to environmental stewardship and long-term sustainability.[29-30]

Enhancing Environmental Stewardship and Marine Ecosystem Sustainability

Molluscs serve as valuable biomonitors and bioindicators of marine pollution, aligning closely with the environmental dimension of the Environmental, Social, and Governance (ESG) framework. These diverse marine organisms are essential to maintaining healthy ecosystems, and their widespread distribution and adaptability make them reliable indicators of marine habitat health.[31] Organizations and governments aiming to demonstrate ESG compliance can utilize mollusc monitoring data to evaluate and mitigate their environmental impact, especially concerning marine biodiversity.[32]

Beyond their role as bioindicators, molluscs are also fundamental to the sustainability of fisheries and aquaculture, both crucial for global food security. However, these industries must balance profitability with environmental responsibility, a core component of ESG criteria.[33] By tracking mollusc populations, stakeholders can encourage more sustainable practices, ensuring that industrial activities support, rather than harm, the long-term health of marine ecosystems.[31]

Due to their sensitivity to environmental pollutants, molluscs provide vital insights into the success of pollution mitigation strategies. Pollution reduction is a critical aspect of ESG frameworks, and monitoring mollusc populations offers companies real-time feedback on these efforts, enabling continuous improvements in environmental stewardship.[34]

Mollusc health and distribution also mirror broader shifts in marine ecosystems, including those influenced by climate change. As companies are increasingly called upon to contribute to climate change mitigation, mollusc monitoring data can help organizations understand and address their environmental impacts.[35-36]

In summary, using molluscs as bioindicators gives businesses and governments a powerful means to demonstrate their commitment to ESG principles. Leveraging the insights these organisms offer enables stakeholders to make informed decisions, reduce environmental footprints, and support the long-term sustainability of marine ecosystems.[37]

The Social Implications of Mollusc Consumption: Mitigating Health Risks and Promoting Community Engagement

The consumption of polluted molluscs poses considerable health risks for local communities, an issue that ESG-conscious organizations must prioritize.[38-39] Exposure to toxic substances, particularly metallic contaminants, can have severe health impacts, especially for vulnerable populations.[40] Moreover, cultural and socioeconomic variations in mollusc preparation methods may influence the degree of exposure to these health risks. To address this, ESG-focused organizations should adopt a comprehensive approach that integrates environmental and social considerations.[50-51]

Understanding the health implications of mollusc consumption within communities is essential. Certain groups, particularly those consuming raw shellfish or including viscera in their diets, face an increased risk of exposure to harmful contaminants.[39] To mitigate these risks effectively, ESG-sensitive organizations should engage with local communities to gain insights into their consumption and preparation practices. Targeted education and awareness initiatives can then be developed to inform at-risk groups and promote safer consumption habits.

Beyond addressing health risks, molluscs also serve as bioindicators, offering valuable insights into the health of marine ecosystems. ESG-conscious organizations can capitalize on this by partnering with local communities to create educational programs that raise awareness of environmental health and encourage public involvement in conservation efforts.[41-42]

By addressing the social aspects of mollusc consumption, ESG-sensitive organizations reduce health risks and foster community engagement. Empowering local stakeholders to actively participate in environmental stewardship improves public health and ecological outcomes, paving the way for a more sustainable future for all.[36,39-40]

Enhancing Corporate Governance through Sustainability Practices

Using molluscs to monitor marine pollution has important corporate governance and sustainability implications. Mollusc-based pollution monitoring provides valuable data supporting regulatory compliance and risk management and enhancing ESG performance.[26,28,34]

Adhering to environmental regulations is essential for companies, and data gathered from mollusc monitoring can be instrumental in demonstrating compliance with environmental standards and guidelines.[26] Organizations incorporating mollusc health into their environmental assessments are better equipped to fulfil regulatory requirements, reflecting their commitment to responsible corporate governance.

Neglecting environmental responsibilities can expose companies to legal, financial, and reputational risks.[29,43] Leveraging molluscs as bioindicators enables companies to better understand their environmental impacts, identify potential risks early, and establish effective risk management strategies.[44] This approach aligns with the growing emphasis on ESG assessments, which consider ecosystem health part of a company's sustainability evaluation. By integrating mollusc-based pollution monitoring into their sustainability frameworks, organizations demonstrate a commitment to comprehensive ESG practices. Addressing these critical environmental indicators can boost ESG performance, foster stakeholder trust, attract investment, and contribute to more sustainable business outcomes.[26,28,44-45]

Knowledge Gaps in Marine Pollution Using Molluscs as Biomonitors and Bioindicators

Extensive research has explored the use of molluscs as bioindicators for marine pollution; however, significant knowledge gaps persist, limiting the effectiveness of molluscs in fully assessing the impacts of pollution on marine environments. These gaps include species-specific differences in pollutant accumulation, which complicate the interpretation of bioindicator data.[24] Certain mollusc species may absorb contaminants more efficiently than others, challenging researchers' ability to generalize findings from studies focused on specific species.[23] Additionally, molluscs are often exposed to multiple pollutants simultaneously, and the synergistic effects of these combined contaminants remain poorly understood. This interaction complicates our understanding of their toxicological processes.[24]

Little is known about molluscs' cellular and metabolic responses to pollutants and their accumulation patterns. Although pollutant concentrations in molluscs can be measured, the complex molecular mechanisms underlying pollutant toxicity remain unclear, limiting insights into pollution's impact at a subcellular level.[22] This lack of understanding extends to broader ecological consequences, such as pollution's effects on mollusc reproduction and population stability over time. Further research is needed to assess how pollution affects mollusc survival, reproductive success, and ecological roles within marine ecosystems.[51-52]

Environmental factors influence contaminant bioavailability and mollusc toxicity, including temperature, salinity, and pH. The interactions between these environmental conditions and pollutants are poorly understood, adding complexity to bioindicator data interpretation.[28] Furthermore, most studies are localized, necessitating more expansive research across diverse ecosystems and geographical areas to produce broadly applicable findings.[52]

Seasonal and long-term variations in pollution levels further complicate the use of molluscs as bioindicators. Understanding how these fluctuations affect contaminant levels in molluscs is essential for developing effective monitoring strategies.[25] Lastly, there is limited knowledge about the direct health risks to humans who consume molluscs from contaminated waters. Molluscs can accumulate substantial amounts of pollutants, but the implications for human health are not fully understood and warrant further investigation.[26]

Addressing these knowledge gaps is essential for improving the use of molluscs as bioindicators in marine pollution assessment and remediation efforts.[24-26] Continued research and monitoring are crucial for enhancing molluscs' reliability as bioindicators and informing more effective conservation and management strategies to protect marine ecosystems.

Conclusion

The literature reviewed on Scopus highlights molluscs' diverse and essential role in advancing environmental sustainability, corporate governance, and community health within the ESG framework. Molluscs, especially marine bivalves, play a vital role in ecosystem health and are increasingly recognized for their potential to support environmental stewardship and sustainability efforts. However, there is a notable gap in research directly linking molluscs to ESG practices, suggesting an area for future investigation. Moreover, mollusc consumption presents important social implications, offering opportunities to mitigate health risks and engage communities. Incorporating molluscs into corporate sustainability practices can strengthen governance by aligning business activities with ecological and social priorities. Additionally, significant knowledge gaps remain regarding the use of molluscs as biomonitors and bioindicators of marine pollution, emphasizing the need for continued research to maximize their effectiveness in marine ecosystem management. In summary, molluscs are a critical bridge between marine health and ESG principles. As bioindicators, they provide valuable insights into the state of marine ecosystems, reflecting the environmental impacts of human activities. This information supports the development of sustainable practices essential to achieving or improving ESG standards. Environmentally, mollusc populations signal biodiversity levels and assist in evaluating the effectiveness of pollution control efforts. Socially, they contribute to community health and economic stability, especially in regions that rely heavily on marine resources. From a governance perspective,

pollution monitoring using bioindicators like molluscs aligns with regulatory adherence, risk management, transparency, and responsible corporate behaviour.

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Ethics Statement
This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement
This study did not involve human participants, and therefore, informed consent was not required.

Author Contributions
- **Chee Kong Yap Kennedy Aaron Aguol, Meng Chuan Ong:** Conceptualization, Methodology, Writing – Original Draft
- **Wan Mohd Syazwan, Rosimah Nulit, Hideo Okamura, Yoshifumi Horie:** Data Collection, Analysis, Writing– Review, Editing
- **Mohamad Saupi Ismail, Ahmad Dwi Setyawan, Krishnan Kumar:** Visualization, Supervision, Project Administration
- **Wan Hee Cheng, and Chee Seng Leow:** Resources, Supervision.

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