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Wei-Bo Chen,
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Imran Khan,
Abdul Wali Khan University Mardan, Pakistan

*CORRESPONDENCE
Alice C. Ortmann
Alice.Ortmann@dfo-mpo.gc.ca

†Retired

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Catalyzing progress in the blue economy through joint marine microbiome research across the Atlantic

Alice C. Ortmann[1*], Kelly D. Goodwin[2], Henk Bolhuis[3], René Groben[4], Thulani Makhalanyane[5], Jeff Bowman[6], Shawn Robinson[7†] and Fabiano Thompson[8]

[1]Bedford Institute of Oceanography, Fisheries and Oceans Canada, Dartmouth, NS, Canada, [2]NOAA Ocean Exploration, National Oceanic and Atmospheric Administration, La Jolla, CA, United States, [3]Department of Marine Microbiology and Biogeochemistry, Royal Netherlands Institute for Sea Research (NIOZ), Texel, Netherlands, [4]Matís ohf., Reykjavik, Iceland, [5]Department of Microbiology, Faculty of Science and The School of Data Science and Computational Thinking, Stellenbosch University, Stellenbosch, South Africa, [6]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, United States, [7]St. Andrews Biological Station, Fisheries and Oceans Canada, St. Andrews, NB, Canada, [8]Institute of Biology, Center for Health Science, Federal University of Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

International agreements recognize the importance of cooperative scientific research to conserve and promote sustainable development of a shared Atlantic Ocean. In 2022, the All-Atlantic Ocean Research and Innovation Alliance Declaration was signed. The All-Atlantic Declaration continues and extends relationships forged by the Galway Statement on Atlantic Ocean Cooperation and the Belém Statement on Atlantic Ocean Research and Innovation Cooperation. These efforts are consistent with programs, actions, and aims of the United Nations Decade of Ocean Science for Sustainable Development. In preparation for implementation of the All-Atlantic Declaration, members of the Marine Microbiome Working Group and the Marine Biotechnology Initiative for the Atlantic under the Galway and Belém Statements respectively, joined forces to call for cooperation across the Atlantic to increase marine microbiome and biotechnology research to promote ocean health and a sustainable bioeconomy. This article reviews the goals of the marine microbiome and biotechnology initiatives under the Galway and Belém Statements and outlines an approach to implement those goals under the All-Atlantic Declaration through a Blue Biotech and Marine Microbiome (BBAMM) collaboration.

KEYWORDS
microbiome, biotechnology, blue bioeconomy, Atlantic Ocean, AAORIA, AORA, Belém

1 Introduction

The Atlantic Ocean holds one of Earth's largest collections of ecological niches, biodiversity, and natural resources. Recognition of the intrinsic and economic importance of this vast resource is well recognized, with calls for resources to be harnessed in a sustainable manner and management decisions to be supported by scientific evidence. In recognition of the connectivity throughout the Atlantic Ocean, international agreements have been signed to foster collaborative science in the region. In particular, the Galway Statement on Atlantic Ocean Cooperation (Galway Statement) was signed in 2013 (European Union, Canada, United States of America, 2013) and the Belém Statement on Atlantic Ocean Research and Innovation Cooperation (Belém Statement) was signed in 2017 (European Union, South Africa, Brazil, 2017). Governance structures were established to implement these agreements, with working groups (WG) formed under the Atlantic Ocean Research Alliance (AORA)[1] for the Galway Statement and joint pilot actions (JPA) formed under the All-Atlantic Cooperation for Ocean Research and Innovation (AANChOR)[2] for the Belém Statement. The WGs and JPAs developed international networks to support research collaborations to foster development and innovation in areas that included seabed mapping, exploration, human capacity, ocean literacy, technology, infrastructure, aquaculture, biotechnology, and marine microbiomes (Polejack and Coelho, 2021; Polejack et al., 2021).

As part of the AORA Coordination and Support Action (CSA), the Marine Microbiome Working Group (MMWG)[3] was formed to champion the inclusion of microbiomes in marine research, develop a strong network of marine microbiome researchers, harness microbiomes to support management, and educate people about the importance of microbiomes in the functioning of a healthy ocean. Under the AANChOR CSA, the Marine Biotechnology Initiative for the Atlantic (BIOTECMAR) was formed to foster collaborations to develop and transfer technology with industrial, medical, or environmental applications involving marine biological resources. BIOTECMAR included goals to increase biodiscovery, improve sustainable aquaculture and food production, and advance technologies for environmental monitoring, complementing the goals of the MMWG.

To facilitate the long-term continuation of these networks, the All-Atlantic Ocean Research and Innovation Alliance Declaration (All-Atlantic Declaration) was signed in 2022[4]. This agreement builds on the previous agreements and expands participation by including new partner countries. Under this declaration, the signatories of the Galway and Belém Statements (European Union, Canada, United States, Brazil, and South Africa) were joined by the Republic of Cabo Verde, Morocco, and Argentina in agreeing to establish the All-Atlantic Ocean Research and Innovation Alliance (AAORIA). AAORIA aims to support sustainable development of the Atlantic Ocean through sharing of knowledge, infrastructure, and human capacity. In addition to the signatories, other countries represented at the All-Atlantic Declaration signing included Colombia, the Dominican Republic, Ghana, Norway, Portugal, and the United Kingdom, indicating a broad understanding of the need for international collaborations to drive marine science research. The AORA MMWG and AANChOR BIOTECMAR began working together to promote an integrated All-Atlantic network as part of the All-Atlantic pledge campaign of 2021[5].

The All-Atlantic Declaration specifically acknowledges the Decade of Ocean Science for Sustainable Development (2021-2030) proclaimed by the United Nations (the Ocean Decade). The vision of the Ocean Decade is to facilitate "the science we need for the ocean we want." The Ocean Decade acknowledges the importance of our oceans in supporting a healthy, sustainable planet, including its roles in human health and security. Under the Ocean Decade, seven outcomes address what is meant by "the ocean we want." This includes oceans that are clean, healthy & resilient, productive, predictable, safe, accessible, and inspiring & engaging. Achieving these outcomes will establish a sustainable blue bioeconomy that supports the wellbeing of both the planet and the human population. A number of microbiome projects are active under the Ocean Decade. For example, the project "Observing and Promoting Atlantic Microbiomes"[6] endorsed under the Ocean Decade's Ocean Biomolecular Observing Network (OBON) Program (Samuel et al., 2021; Leinen et al., 2022) is led by the AORA MMWG to implement actions of the Marine Microbiome Roadmap (Bolhuis et al., 2020).

2 Marine biotechnology and microbiome initiatives under Belém and Galway

Marine microbiomes are composed of the smallest organisms in the oceans, such as viruses, prokaryotes, and eukaryotic microbes, including phytoplankton. Understanding marine microbiome diversity and function is critical to the sustainability of the Atlantic Ocean. In addition to ecosystem services, marine microbiomes can provide direct economic benefit through marine biotechnology. Marine biotechnology includes the exploration of marine natural products, industrial applications of microbial processes, and aquaculture (Thompson et al., 2018). The All-Atlantic BIOTECMAR Roadmap and Action Plan (Thompson F et al., 2023) (the Biotechnology Action Plan) outlines actions and targets toward developing a sustainable marine biotechnology and

1 https://allatlanticocean.org/working-groups/

2 https://allatlanticocean.org/all-atlantic-joint-actions/

3 https://www.marinemicrobiome.org/

4 https://allatlantic2022.com/

5 https://www.allatlantic2021.eu/pledge/pledge-list/#submitted

6 https://oceandecade.org/actions/observing-and-promoting-atlantic-microbiomes/

bioeconomy enterprise across the Atlantic. Topics include food security, biodiscovery, and the role of biotechnology in environmental health, including mitigation of problems exacerbated by climate change and pollution. Goals include building a strong network to support start-ups and to foster innovation within existing companies. The plan calls for studies on microbial pathogens, microbial biodiversity-driven biodiscovery, and utilization of microbiomes as biosensors to monitor the environment (Polejack and Coelho, 2021; Polejack et al., 2021).

The AORA Marine Microbiome Roadmap (Bolhuis et al., 2020) was developed by the MMWG in collaboration with microbiome researchers and policy makers across the EU, Canada, and the US through a series of consultations in 2019—2020. This document calls for cooperation across the Atlantic to increase marine microbiome research to promote a healthy ocean and sustainable bioeconomy, complementary to many aspects of the Biotechnology Action Plan. The Marine Microbiome Roadmap organizes research goals and priorities around the following four themes: Environment and Climate, Food Value Chain, Biodiscovery, and Cross-Cutting Challenges (Figure 1). Each theme lists short-, medium-, and long-term actions identified by experts in the field as necessary steps to advance marine microbiome science forward. Themes of the Roadmap are briefly summarized here.

2.1 Environment and climate

From coasts to open ocean and from the surface microlayer to the deepest trenches, microbes permeate every habitat, plant, and animal. Microbes are the base upon which ocean food webs are built, and their activities influence the chemistry and physics of our planet's climate system (Figure 2). Their diverse roles make them both drivers and indicators of ocean health. These roles include helping pump carbon from the air into the sea (carbon sequestration) and consuming methane before it can be released into the atmosphere. Simultaneously, microbes recycle waste products, break down pollutants, and supply food webs and fisheries with essential nutrients. On the other hand, some marine microbes threaten ecosystem services by producing toxins, causing diseases, and creating hypoxic or anoxic zones.

While understanding has grown regarding the immense taxonomic and metabolic diversity of the marine microbiome, our ability to observe at the scale enjoyed by physico-chemical ocean observation efforts is relatively underdeveloped (Tara Ocean Foundation, Tara Oceans, European Molecular Biology Laboratory, 2022). Coverage of the ocean by molecular observations - the gold standard for characterizing microbiomes - remains poor, with large geographical gaps and low replication of measurements over time, especially in the southern hemisphere. As a consequence, we have poor knowledge on how diversity, function, and rates vary across time and space, and we lack understanding of how to connect the growing number of 'omics studies (e.g., genomic, proteomic, metabolomic) to measurements of rates and cycles (e.g., nitrogen fixation, primary productivity, carbon sequestration) (Coutinho et al., 2018). Priorities for experiments and field observations include areas undergoing rapid change, prone to biological threats (e.g., harmful algal blooms, pathogens), chemical hazards (e.g., anthropogenic chemicals, hypoxia or anoxia), hotspots of biodiversity, potential for high carbon capture and/or release, under sampled habitats (e.g.,

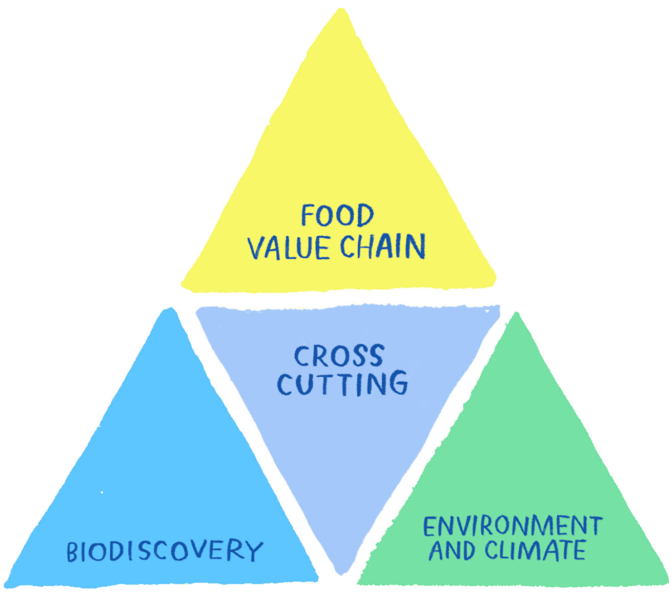

FIGURE 1
Thematic areas of the AORA Marine Microbiome Roadmap. Illustration by Rán Flygenring.

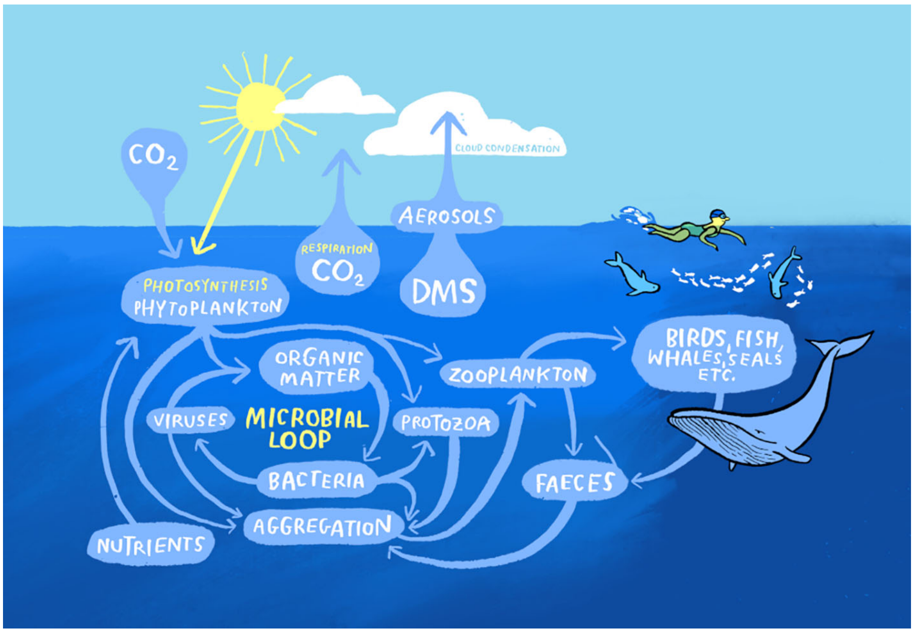

FIGURE 2
Microbes influence the chemistry and physics of Earth and underpin all life in the ocean. Illustration by Rán Flygenring.

sediments, especially in the deep-sea), and those areas experiencing minimal human impact to establish baselines for ecological restoration.

Mapping Atlantic microbiomes and their connectivity and variation in time and space is a main goal within the environment and climate theme of the Marine Microbiome Roadmap. However, the high costs of ship-based operations limit microbiome observations for all countries and severely restrict participation by many others. Improving geographical coverage of microbiome diversity and function studies is imperative for integration of microbiome data into climate and sustainability models (American Society for Microbiology, 2022; Tara Ocean Foundation, Tara Oceans, European Molecular Biology Laboratory, 2022; Tiedje et al., 2022) but needs to be done in an inclusive way that respects and includes researchers in underrepresented regions. The need to increase biological observations in a cost-effective manner is driving technological advances to improve remote and autonomous collection of samples and data (Beatty et al., 2021; Den Uyl et al., 2022).

Other goals under the Environment and Climate theme include: identifying novel microbial indicators of ocean health and change, improving capacities for the prediction of the future state of ocean health, characterizing and quantifying microbiome-related ecosystem services to societies and providing insights into drivers and future trajectories of these services, and providing responses to challenges identified by the Intergovernmental Panel for Climate Change (IPCC) and the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES). Long term action items include maintaining quality-controlled maps of Atlantic microbiomes that are fully integrated with other ocean data layers. Desired outcomes of mainstreaming microbiome observations into existing ocean observation efforts and integrating microbiome dynamics into ecosystem models include improving the ability to predict and respond to climate variation and ecological hazards (Tara Ocean Foundation, Tara Oceans, European Molecular Biology Laboratory, 2022).

2.2 Food value chain

Marine ecosystems supply food needed to support a growing human population. At the same time, a large number of fisheries are stressed, and the sustainability of industrial-scale aquaculture practices are being questioned (Ahmed et al., 2019; Jiang et al., 2022). Furthermore, climate change is impacting species ranges and may affect pathogen occurrence in aquaculture and wild-caught systems (Thompson C et al., 2023). Rising sea levels in some regions are leading to the salinification of coastal lands, posing challenges for traditional agriculture. Under these strains, understanding the roles and impacts of marine microbiomes on food production systems can help identify solutions and innovations that can increase the sustainability of resources and provide economic stability to food producers (Tara Ocean Foundation, Tara Oceans, European Molecular Biology Laboratory, 2022).

The focus of the Food Value theme in the Marine Microbiome Roadmap is to develop solutions that promote a sustainable marine food market. Goals for the food value chain theme include: advancing the scientific understanding of microbiomes associated with or applied to marine food production to be on par with that of agricultural and human systems, developing novel technologies to apply microbiomes in the production of healthy, eco-friendly marine food, integrating microbiome monitoring into the management of sustainable marine food production, and providing free exchange of knowledge and technology to increase the ability of food producers (at all scales) to leverage microbiome technologies to promote stock health and productivity.

2.3 Biodiscovery

Marine microbes exist and thrive in a variety of challenging environments. The high diversity and unique nature of marine microbiomes suggests they have the capacity to produce compounds with novel antimicrobial, antibiotic, anticancer, and other useful properties (Paoli et al., 2022). However, the potential for marine microbiomes to fuel new products and innovations remains largely untapped. Focus on individual, culturable strains has limited biodiscovery because few marine microbes can be cultivated in isolation (Figure 3) and bioactive compounds may only be produced when in consortia. The Marine Microbiome Roadmap calls for bioprospecting efforts to go beyond the traditional focus on single microorganisms, toward discovery based on complex interactions involving whole microbiomes. Achieving this objective will require developing methods to analyze and model microbial communities, including metabolic profiles.

Propelling marine biodiscovery to provide new sources of value to society will require inspiring entrepreneurship and developing the next generation of innovators. Access to both technical (e.g., bioprocessing, bioinformatics) and business (e.g., contracts, intellectual property) training are needed to prime the research transition pipeline. Collaborations between microbiome researchers and industry, along with governmental cooperation to develop regulations can ensure that biodiscovery and bioprospecting is a driver of a sustainable blue bioeconomy.

2.4 Cross-cutting challenges

Recognizing that food security, biodiscovery, and environment and climate issues are interconnected, as are all of the processes in the marine environment, the fourth theme focuses on challenges that cut across all marine microbiome research. For example, research to understand microbial roles in climate regulation can inform developments in aquaculture and provide resources for drug discovery. Beyond the microbial and biotechnology realms, microbiome research can inform a broad range of topics including climate, oceanography, sustainable resource use, and pollution control. The eight cross-cutting challenges of the Marine Microbiome Roadmap are to: 1) Demonstrate the socio-economic value of marine microbiomes to translate the science of marine microbiomes into investable propositions, 2) Increase our capacity to share infrastructures to better explore, monitor, and engineer solutions, 3) Transfer technology across science and industry, 4) Assess the risks and ethics related to microbiome science & technology, 5) Preserve bioresources and share their benefits, 6) Spark fascination about marine microbiomes (Figure 4), 7) Develop standards and common methodologies, and 8) Adopt best practices and the FAIR principles for scientific data.

3 Progress implementing Atlantic Ocean marine microbiome and biotechnology initiatives

3.1 Cross-cutting

Activities of the MMWG and BIOTECHMAR have worked to build a network that spans governments, academia, and industry to demonstrate the socio-economic value of marine microbiomes. The diversity of this network across the Atlantic provides a range of perspectives and experiences necessary to develop a sustainable blue bioeconomy. An in-depth symposium was hosted at an American Society of Microbiology[7] meeting that brought together researchers from the US, Europe, South America, and South Africa. Earlier events hosted in association with the All-Atlantic Research Forum[8] achieved participation of over 250 people representing North and South America, Europe, Africa, and Asia which demonstrates that marine microbiome researchers and industry have an interest in building such a network across the Atlantic.

Harmonized microbiome sampling and data methods underpin the research advances and innovations needed to support a sustainable blue bioeconomy. To promote the development of standards and common methodologies, the MMWG sponsored the Frontiers in Microbiology research topic "Marine Microbiomes: Towards Standard Methods and Best Practices" (Goodwin and Lacoursière-Roussel, 2023). In particular, harmonized methods are essential in establishing time series data. These data provide the means to measure changing conditions against baselines; critical for integrating microbiome science into decision making. Papers included in this issue reviewed best practices for microbiome sample collection (Patin and Goodwin, 2023) and outlined a platform to share community-endorsed protocols (Samuel et al., 2021) through Better Biomolecular Ocean Practices (BeBOP)[9], a UN Decade endorsed effort dedicated to standardizing the application of molecular tools in marine science. A key goal of these efforts is to create and manage microbiome data that fits the FAIR principles, meaning the data are Findable, Accessible, Interoperable and Re-usable (Blumberg et al., 2021).

Ocean literacy is a challenge across the marine sciences. Microbes and their important roles in ocean health are not always included in education materials (Tara Ocean Foundation, Tara Oceans, European Molecular Biology Laboratory, 2022). Additionally, due to the perception of microbial organisms as 'germs' that make people sick and need to be killed, it is important to share the positive impacts microbiomes have in the oceans. For example, the immense hidden diversity of the microbial world yet to be explored, "microbial dark

7 https://www.abstractsonline.com/pp8/#!/10789/session/207

8 https://www.allatlantic2021.eu/wp-content/uploads/2021/04/Speakers-Microbiome.pdf

9 https://www.oceanbestpractices.org/about/task-teams/obps-task-team-21-03-omics-edna-protocol-management/

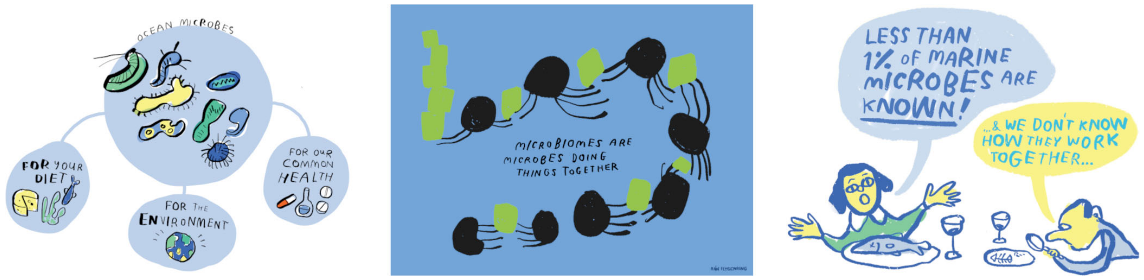

FIGURE 3
The marine microbiome represents an untapped resource for biodiscovery. Developing the ability to analyze and manipulate microbial consortia may be key to harnessing this resource. Illustrations by Rán Flygenring.

FIGURE 4
Example of art used to spark fascination and promote ocean literacy. Illustration by Rán Flygenring.

matter", is a concept to spark fascination about marine microbiomes. To that end, combining art and science is an effective means to communicate complex concepts and promote ocean literacy (Figures 1-5). The MMWG supports artists and content creators that produce informative illustrations, a series of animated short videos, and a downloadable coloring book (available at www.marinemicrobiome.org).

3.2 Environment and climate

Progress addressing goals in the Environment and Climate theme has been made through the activities of international projects. For example, AtlantECO[10] is a large EU-funded project with connections to AORA and AANChOR. Goals of the project include understanding microbiomes to support the blue bioeconomy, understanding microbiome interactions within the plastisphere, and establishing a better understanding of the links between land, oceans, climate, and human activity. Microbial diversity investigations through AtlantECO have provided snapshots of community diversity across time and space, primarily measured with 'omics tools (e.g., Benedetti et al., 2021; Brandão et al., 2021; Chaffron et al., 2021; Endrédi et al., 2021). Consistent with the roadmaps, AtlantECO aims to increase marine microbiome observations in the southern oceans, including the coasts of South America. The MMWG worked to increase east-west and north-south interactions by helping staff on a cruise to the Southern Ocean conducted by the Mission Microbiomes[11] component of AtlantECO.

As we develop a better understanding of microbiomes representing healthy ecosystems versus polluted or stressed ecosystems, we can begin to incorporate microbiomes into

10 https://www.atlanteco.eu/

11 https://fondationtaraocean.org/en/expedition/mission-microbiomes/

FIGURE 5
Illustrations depicting concepts related to integrated multitrophic aquaculture. Illustrations by Rán Flygenring.

monitoring programs, which is one of the goals of both the Marine Microbiome Roadmap and the Biotechnology Action Plan. As part of OBON, the MMWG's Ocean Decade Action encourages the inclusion of microbial parameters into long term monitoring studies. This has been helped by the push to include microbial parameters as Essential Biodiversity Variables[12] to measure change, and the establishment of microbial biomass and diversity as Essential Ocean Variables by the Global Ocean Observing System (GOOS) (Buttigieg et al., 2018; Muller-Karger et al., 2018). These concepts also are foundational to the Omic Biodiversity Observation Network (Omic BON) recently formed under the Group on Earth Observations Biodiversity Observation Network (GEO BON) (Meyer et al., 2023).

3.3 Food value chain

When different species of different trophic levels are farmed together, waste from one level feeds the next, creating the "circular economy" that decreases the carbon footprint of the aquaculture facility (Figure 5). For example, integrated multitrophic aquaculture (IMTA) efforts piloted by the ASTRAL Horizon 2020 project work to incorporate low trophic levels and synergistic interactions among species within single facilities. Ongoing activities within programs such as AquaVitae or INNOAQUA promote farming species lower on the food web (e.g., microalgae) to improve the food value chain and microbiome enhancements to improve aquaculture (e.g., Silva et al., 2022; Holanda et al., 2023), while the MASTER project developed probiotics to enhance growth of Arctic char (Knobloch et al., 2022). Activities from programs such as SIMBA have explored market forces that can affect the willingness of farmers and consumers to adopt microbial-based solutions (Ali et al., 2021; Tensi et al., 2022).

3.4 Biodiscovery

As new techniques and approaches are applied to delve deeper into understanding the diversity and function of marine microbiomes, we are uncovering novel resources ripe for fueling innovation in medicine, health, ecological understanding, and industrial applications. The diversity of unknown genes identified through ocean surveys (e.g., Sargasso Sea, Tara Oceans) represent the potential for new metabolic processes and biological molecules to be identified (Tara Ocean Foundation, Tara Oceans, European Molecular Biology Laboratory, 2022). Marine microbiomes have already been a source for bioprospecting resulting in the development of an algal-derived nasal spray that is effective against the SARS CoV-2 virus (Figueroa et al., 2021), and metabolites from cyanobacteria are being explored for treating viral infections and skin cancer (Prabhu et al., 2022). Following the initial discovery of the CRISPR/Cas system in bacteria and archaea, the CRISPR-Cas9 genome editing technique has significantly changed how some medical and agricultural research is carried out. Through exploring marine microbiomes, novel and diverse cyanobacterial CRISPR/Cas systems have been identified which may lead to further advances in genome editing (e.g., Cai et al., 2013; Kalwani et al., 2020).

Microbes play a role in biodegradation of pollutants including oil, plastics, and 'forever' chemicals, which can provide the basis for engineering new bioremediation strategies (reviewed in: Hazen et al., 2016; Ganesh Kumar et al., 2020; Wackett and Robinson, 2020). Additionally, marine microbiomes have provided novel food additives, high-value food products, and can produce compounds for a range of industrial applications (e.g., bioplastics, nanomaterials) (Manivasagan and Oh, 2016; Cesário et al., 2018; García-Depraect et al., 2021). There is also research focusing on how microbial processes could be used to develop carbon capture or carbon sequestration technologies to help mitigate climate change (Greene et al., 2022).

4 Actionable recommendations: All-Atlantic Blue Biotechnology and Marine Microbiome framework

The AAORIA highlights the need to address the considerable challenges facing the Atlantic basin at local and regional scales and acknowledges important linkages with the polar seas. Challenges include climate change, pollution, overexploitation of resources,

12 https://geobon.org/ebvs/what-are-ebvs/

and other anthropogenic stressors. The establishment of a Blue Biotechnology and Marine Microbiome (BBAMM) action group under the AAORIA would support biotechnological discovery and innovation, ocean health, and sustainable food production. Our vision to achieve a sustainable blue bioeconomy focuses on creating inclusive research, entrepreneurship, and innovation programs that build capacity and involve local human resources for the purpose of creating sustainable bioeconomies and a healthy planet (Thompson et al., 2017). Working together under an All-Atlantic framework, we propose the following three priority actions.

4.1 Build capacity

To continue advancing marine microbiome research, we need to increase human capacity and exchange of knowledge. We propose developing bidirectional exchanges within collaborative research partnerships. These partnerships would span north and south as well as east and west and be designed to not only transfer technical skills but build personal relationships for early career scientists. Through exchange of differing perspectives, we hope to foster understanding of how research environments vary across countries. Mutual understanding can identify new ways to address needs, such as the development of new technologies, redesign of older technologies, or effective sharing of resources and knowledge.

Building capacity through bidirectional exchanges can help address the high costs of marine microbiome research through sharing of infrastructure, whether that facilitates sampling (e.g., sharing vessels and sample equipment) or access to data and computing capacity. Exchanges can be used to develop collaborations outside of traditional marine microbiome research groups. These collaborations could leverage research in human genomic and medical fields, engineering, modeling, and artificial intelligence to develop new techniques and approaches to marine microbiome research. Collaborations with governments and industry can address policy and economic challenges in developing a sustainable bioeconomy.

4.2 Ocean literacy and appreciation of marine microbiomes

Efforts to enhance ocean literacy have been relatively successful, although many remain unaware of the important roles microbes play in ocean health and the need to include microbial dynamics in earth system models. To facilitate inclusion of microbiome data in ecosystem and sustainability models, conversations between modelers and microbiome researchers can be initiated. Microbial ecologists need to understand the types and formats of data needed and modelers need to understand where and how to include such data.

Beyond sharing with fellow scientists the importance of marine microbiomes to the ocean system, there is a need to reach governments, policy makers, industry, and the general public. Approaches include developing materials designed to expand collaborations with museums and educational efforts and to enhance our social media presence. Goals include emphasizing the role of microbes in ocean functioning and health, as well as the economic value they could have as part of a sustainable blue bioeconomy.

4.3 Coordinated research

The activities, diversity, and impacts of marine microbiomes cross international boundaries and affect human populations far from the oceans. Analogously, the research to understand marine microbiomes also must cross international boundaries. Along with the All-Atlantic framework, several bilateral and multilateral agreements exist that can be utilized to support fully integrated research programs. For example, the BioGeoSCAPES[13] program is an emerging international effort to quantify the environmental and biological controls of biogeochemical cycling. This effort aims to carry out research from local to global scales linking microbiome data to micronutrient and tracer data in a way that can be adopted into ocean models. This program, following similar successful programs focused on chemical and physical processes (e.g., JPIOceans and GEOTRACERS), should generate a new understanding of ocean processes and the characteristics of a healthy ocean able to support a sustainable blue bioeconomy. Efforts are needed to ensure that developing south Atlantic countries can contribute to such efforts, with significant funding needed for countries such as Brazil, Argentina, Colombia, the Dominican Republic, Ghana, Morocco, and South Africa (Overbeck et al., 2018; Quintans-Júnior et al., 2020).

Large-scale microbiome projects funded by the EU-led Horizon 2020 and Horizon Europe initiatives have been important contributors to progress on the AORA and AANChOR microbiome and biotechnology initiatives to date. However, scientists from countries such as the US have not been able to receive funding from those sources, which hampers the ability to truly co-design and co-execute scientific research. We encourage the development of financial mechanisms and new agreements that would enable truly collaborative and coordinated research across the Atlantic. This would facilitate resource sharing, whether it is making technologies more accessible or sharing infrastructure such as equipment or ships. As the UN Ocean Decade progresses and AAORIA expands, Atlantic nations have an opportunity to support international and interdisciplinary ocean research. Ultimately, by coordinating research funding, we can more efficiently use the funds to carry out ocean research, minimize duplication of effort and support co-design of research from day one, which will help us to develop an inclusive, equitable and sustainable blue bioeconomy.

5 Conclusions

To foster a sustainable blue bioeconomy across the Atlantic, we will need to (i) continue to build a strong and inclusive research network, (ii) develop coordinated international research spanning the whole Atlantic Ocean, and (iii) support improved ocean literacy and appreciation for marine microbiomes. Aligned with the

13 https://biogeoscapes.org/

AAORIA values of international partnerships, the establishment of a Blue Biotechnology and Marine Microbiome action group would:

- Foster collaborative networks across government, academic, and private sectors to promote blue biotechnology and marine microbiome solutions to challenges facing the environment and society.
- Facilitate collaborations to develop research programs across the Atlantic on marine microbiomes, aquaculture, drug discovery and development, and other relevant marine technologies to enhance the blue economy, including those focused on carbon drawdown.
- Foster mechanisms of technology transfer across sectors and countries and promote the development of new marine biotechnology companies at the Atlantic Ocean level.
- Promote networking and engagement of partners to build capacity and support training in ocean sciences and technology and ocean leadership to build an inclusive and diverse community of practice.
- Spark fascination and develop ocean literacy around blue biotechnology, aquaculture and microbiomes, and their potential to address current challenges.

Author contributions

AO: Conceptualization, Writing – original draft, Writing – review and editing. KG: Conceptualization, Writing – review and editing. HB: Conceptualization, Writing – review and editing. RG: Conceptualization, Writing – review and editing. TM: Conceptualization, Writing – review and editing. JB: Conceptualization, Writing – review and editing. SR: Conceptualization, Writing – review and editing. FT: Conceptualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

RG is employed by Matís ohf.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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