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The southern gap in ocean microbiome science

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Abstract
The ocean microbiome is at the forefront of science, and although most of the global ocean lies in the southern hemisphere, research efforts have historically been concentrated in the northern hemisphere, leaving important southern regions underexplored. Here, we address this geographic gap in ocean microbiome research, including sampling efforts, access to technology, and expert human resources. We showcase north–south and south-south collaborations and discuss the main challenges posed by parachute research, and collective efforts to avoid it and achieve shared capacity, equitable access to knowledge, and shared benefits. Our recommendations emphasize the importance of actively involving students and researchers from low- and middle-income countries from the global south in co-designing global ocean microbiome research.

Keywords North–south collaboration, Sequencing, Omics, Parachute science, Helicopter science, Equitable partnerships, Reflexivity statements

Main text

The power of the ocean

The ocean is vital to human existence. It is the largest ecosystem on Earth and plays a crucial role in regulating our climate by absorbing carbon and heat, generating about half of the world's oxygen, and providing food for billions of people [1]. It offers alternative energy sources and valuable mineral and genetic resources that provide new materials, medicines, and other innovations [2].

There is also a deep historical relationship between maritime power and economic prosperity, marked by the association of seapower with trading values, policy and military control [3]. From the dawn of civilization, nations have sought to command the seas. Navigation technology has long been a means for wealthy and powerful nations to demonstrate and expand their influence [5]. Today, state-of-the-art sequencing technologies are mostly concentrated in a limited number of high-income countries, leaving vast southern regions with fewer dedicated resources for ocean exploration.

The larger part of the global ocean is found in the southern hemisphere. Yet, sampling efforts are much higher in the northern hemisphere, with vast unexplored areas in the southern hemisphere (Fig. 1), including hotspots for our understanding of biogeochemical cycles and ocean circulation, such as the Southern Ocean, the Benguela upwelling, or the Amazon plume.

Some of the most promising opportunities in the ocean are found within the microbiome bioprospection for genes of human interest in the most diverse fields, from medicine to environmental remediation [6, 7]. The ocean

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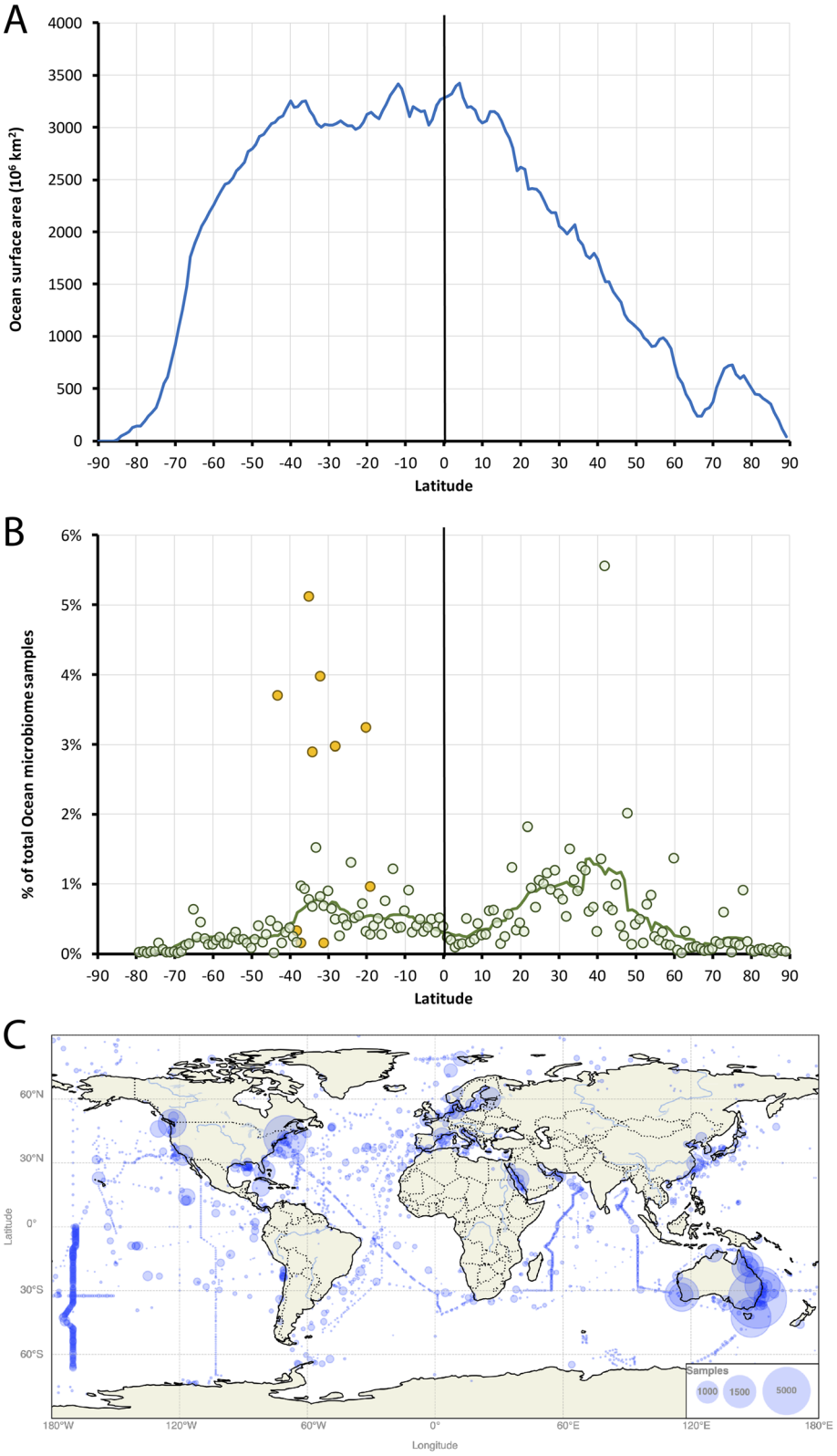

Fig. 1 (See legend on next page.)

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Fig. 1 The gap: unbalanced sampling effort: **a** The ocean covers approximately 71% of the Earth's surface. However, the distribution between the Northern and Southern Hemispheres is not equal: 60% of the surface area in the Northern Hemisphere is ocean, while in the Southern Hemisphere, 80% of the surface area is ocean. **b** The opposite trend can be observed in ocean microbiome sampling efforts. Accounting for 63.606 georeferenced samples (metagenomes or amplicons) from 485 sequencing projects deposited in the European Nucleotide Archive (ENA), only 29.6% of total samples come from the Southern Hemisphere (excluding Australia, orange dots, which alone accounts for 23.5% of samples, due to an extensive monitoring program that includes the collection of genetic microbiome data [5], compared to 46.9% in the Northern Hemisphere. The green dots represent the proportion of the total number of samples at each degree of latitude, while the green line shows the moving average to illustrate the trend in sampling effort across latitude. In the figure **c**, the size of the blue dots is proportional to the number of samples collected at each location in the global ocean

microbiome plays a crucial role in nutrient cycling, carbon sequestration, and climate regulation, helping to maintain the Earth's ecological balance [8]. However, the ocean faces numerous threats from human activities, including climate change, overfishing, pollution, and acidification. These actions have not only altered the ocean, but also compromised its health, and its ability to provide benefits to humanity [9]. Consequently, recognizing the ocean as a global common underscores the urgent need to protect and preserve its health and sustainability for future generations [10].

Effective management and governance of human activities are essential to maintain ocean health, resilience, and function, ensuring that it continues to provide benefits safely to humankind [10]. This requires robust scientific research to inform decision-making processes. Science is crucial for understanding oceanic functions, predicting future ocean states, guiding the regulation of human activities, establishing safety and warning systems, and aiding society in adapting to environmental and climate changes [11].

Ocean science requires advanced technology, equipment, and data sharing to explore the complexities of the globally interconnected ocean. Ocean observations and monitoring involve various research platforms, including moored and drifting buoys and satellite imagery, often managed by intergovernmental coordination mechanisms. The ARGO program (https://argo.ucsd.edu), which deploys a global array of autonomous profiling floats to collect high-resolution temperature and salinity data, and the Southern Ocean Observing System (https://soos.aq) are good examples. This level of scientif ic deployment is costly and requires coordination across large spatial and temporal scales. Collaborative efforts and co-investment among nations can be supported through science diplomacy, which merges science and international relations [12].

Given these challenges, it is imperative to foster equitable north–south collaborations and reinforce south-south networks. Strengthening these relationships is essential for addressing global challenges, ensuring that the benefits of ocean science and its applications are shared more equitably across all regions, and empowering low- and middle-income nations to play a more active role in ocean governance and exploration [13].

We cannot change history, but we can shape the future: combatting parachute research

Ethics in scientific collaborations has become a major concern in recent years across many research areas [14]. A common practice in the past, where researchers from developed nations would travel to remote regions, collect samples or make observations, and publish results without involving local researchers or considering local populations, is no longer acceptable. Such practices, known as parachute or helicopter research, have been widely criticized in many fields [15–17], but they are still too common.

Analyses of published literature show a dominance of affiliations from outside the regions studied, underscoring systemic imbalances in research leadership and opportunities for meaningful local participation. This practice is clearly demonstrated when examining author affiliations in studies focused on two critical hotspots for marine research in the southern hemisphere: the Benguela upwelling and the Amazon plume. In these regions, analyses of published literature indicate a pronounced dominance of leading authors affiliated with institutions from northern hemisphere countries. Furthermore, more than half of the peer-reviewed articles addressing these regions lack involvement of researchers affiliated with institutions located within the respective countries. A substantial number of studies conducted in the Benguela upwelling region do not involve researchers from Namibia, Angola, or even South Africa, despite these countries bordering the upwelling zone. Similarly, research on the Amazon plume often excludes authors from neighboring countries or institutions, despite its direct implications for local ecology, conservation, and environmental policies. This practice not only perpetuates geographic disparities in scientific expertise but also limits the opportunities for local researchers to contribute meaningfully, influence research priorities, incorporate essential local knowledge, and derive benefits from research conducted in their own regions. Moreover, ignoring local expertise can lead to missed opportunities for deeper insights and more effective, contextualized findings (Fig. 2).

Another common practice is the inclusion of local researchers solely to fulfill permitting conditions established by national regulations, such as Brazil's biodiversity law, which implemented a compliance mechanism

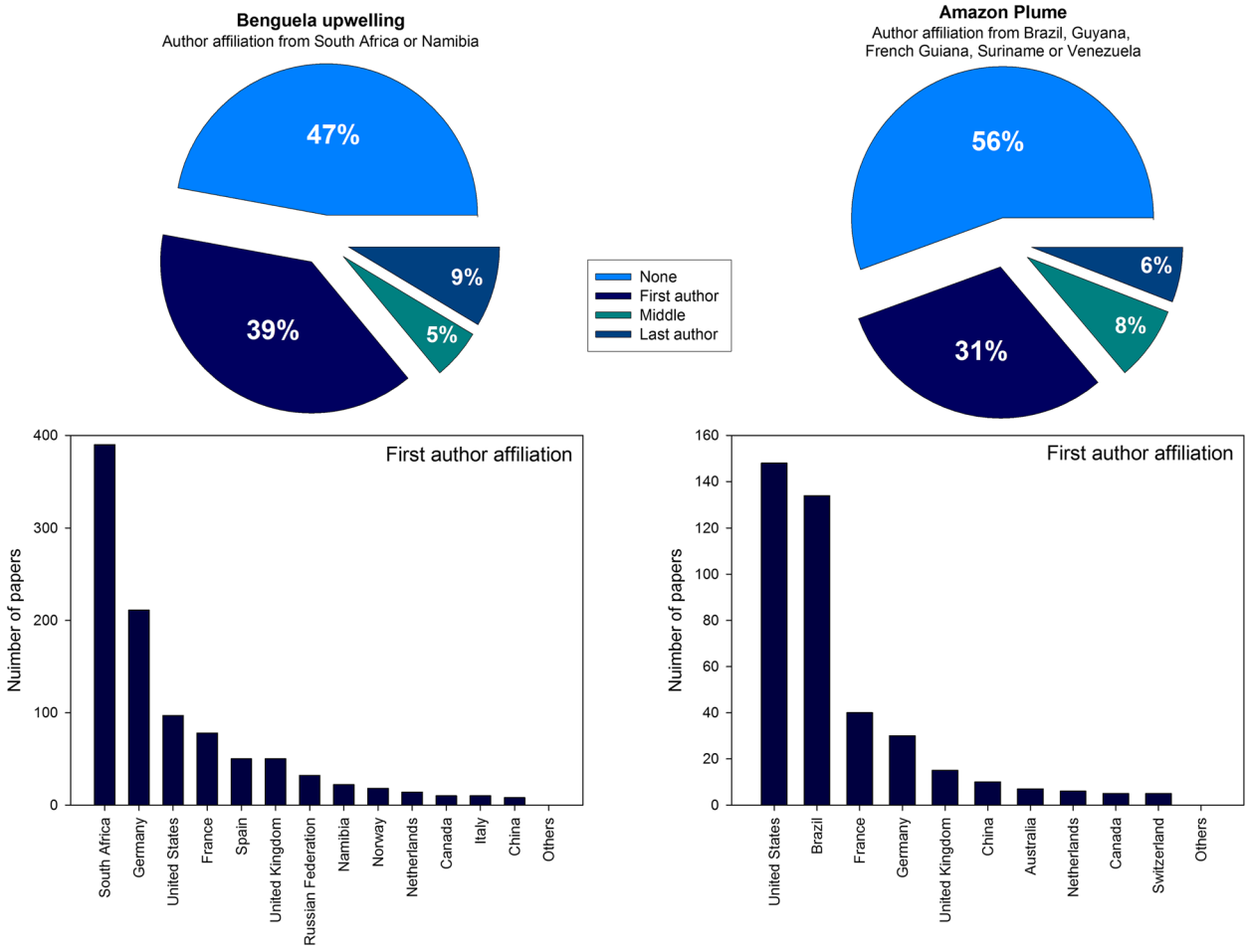

Fig. 2 Authors' affiliation countries declared in published scientific papers on two hotspots of oceanographic research, the Benguela upwelling (left panels) and the Amazon plume (right panels). In most published papers, the first author is not from countries surrounding the marine hotspot, and northern hemisphere countries are on the top of the list. Scopus search using the terms: "Benguela AND upwelling" and "Amazon AND Plume," respectively, conducted in May 2024

to regulate the access to genetic resources and associated traditional knowledge (SisGen), ensuring benefit-sharing for biodiversity conservation and sustainable use. Although Brazilian law does not explicitly require co-authorship in scientific publications, the involvement of Brazilian scientists is mandatory for obtaining permits to conduct sampling within the country. Consequently, international groups often include local researchers as coauthors primarily to meet these permit requirements. Adding authors solely to meet permitting requirements, without fostering genuine collaboration, does little to advance scientific capacity in the global south. Such practices may be considered ethically questionable, as they undermine authentic partnerships and fail to meaningfully engage local expertise. Furthermore, these superficial collaborations are difficult to identify and can complicate efforts toward promoting equitable and ethical scientific collaboration.

Recent efforts, mainly in the health research community, have shown that promoting equity in international collaborations can be systematically strengthened through structural mechanisms, such as the adoption of reflexivity statements [18]. These statements require authors to explicitly reflect on and document how local researchers were engaged in setting research priorities, designing studies, collecting and analyzing data, and sharing credit and benefits. Implementing a similar practice in oceanography could be a valuable step toward discouraging parachute science and promoting truly collaborative research. Journals, funding agencies, and research consortia could encourage or require reflexivity statements to make power dynamics within collaborations more transparent and accountable. Building on this principle, it is crucial to advocate for the continuous involvement of local researchers in defining research priorities. Local expertise is essential to understanding the usefulness of the research being conducted, as they

possess the insight into where, how, and when it is best to sample, based on their knowledge of local sites. A common challenge, however, is reconciling differing research goals and contexts across collaborations: Large-scale global syntheses (e.g., the Tara Oceans expedition) are often associated with initiatives from the global north, whereas place-based studies (e.g., fisheries management) are more frequently prioritized in low- and middle-income countries from the global south. For instance, while climate change is a pressing global issue, researchers in many developing countries often face immediate challenges such as water security, sanitation, or pollution control. It is difficult to argue for investment in long-term climate change research when many communities still lack access to basic sanitation or reliable environmental monitoring. Although less common, cross-cutting examples also exist, for instance, Brazil's PROANTAR program, which contributes to global polar and climate research, or other northern-led conservation projects in the global south. These examples illustrate that global and local approaches are not incompatible but rather complementary. Building on this complementarity, research frameworks that intentionally integrate both perspectives can enable "big science" to advance global understanding while simultaneously ensuring meaningful local impact. Oceanographic research inherently requires international collaboration, making it crucial for the marine research community to commit to avoiding parachute research or any kind of unethical practice in collaborative initiatives. The All Atlantic Ocean Research Alliance (https://allatlanticocean.org), supported by the Galway Statement (2013, https://ec.europa.eu/commission/presscorner/detail/en/ip_13_459), the South-South Framework for Scientific and Technical Cooperation in the South and Tropical Atlantic and the Southern Oceans (2017, http://www.dst.gov.za/images/South--South-Framework-for-Scientific-and-Technical-Cooperation-in-the-South-and-Tropical-Atlantic-and-Southern-Oceans.pdf), and the Belém Statement (2017, http://www.atlanticresource.org/aora/belem-statement/), emerged at the UN Decade of Ocean Science for Sustainable Development (2021–2030) as a landmark initiative unifying the Atlantic Ocean as a whole [13]. Such initiatives, involving researchers from both the north and south, represent a constructive and necessary path forward for inclusive ocean science.

The AtlantECO project, funded by the European Union within the All Atlantic Ocean Research Alliance framework, is a success story that brought together a network of researchers from Europe, South America, and South Africa. The project's success was largely due to its bottom-up approach in defining research goals. Part of the Tara schooner Mission Microbiomes was conducted within the scope of AtlantECO. The ship sailed along the South American and African coasts of the Atlantic, combining research activities with outreach during several port calls, involving the local research community and the general public (Fig. 3). The entire cruise focused on the tropical, equatorial, and southern regions of the ocean, with all 168 sampling stations, resulting in over 25,000 collected samples, located between latitudes 65°S and 15°N. Ten students and postdoctoral researchers from the global south participated on board.

Research activities were organized as topical studies in various oceanographic regions, where local and foreign researchers were invited to virtual meetings to synthesize existing knowledge and identify gaps and scientific questions that the mission should address before the ship's arrival. For instance, in the Amazon plume topical study, researchers from Brazil, Europe, and the U.S.A. participated in several virtual meetings to discuss the existing scientific knowledge and identify research gaps. These discussions addressed both global issues, such as the Amazon plume's role as a potential carbon sink hotspot, and local concerns currently under debate in Brazil, including the potential impacts of offshore oil drilling in the region. This topical study focused on understanding the influence of the Amazon plume on ocean productivity and biogeochemical cycling. Six Brazilian students participated directly in this leg of the cruise, engaging in both sampling and analyses. Similarly, the Benguela upwelling topical study brought together scientists from South Africa and Namibia to investigate the dynamics of microbial communities in relation to nutrient upwelling, carbon fluxes, and episodes of oxygen depletion that lead to mass mortality events on the coast. These collaborative efforts offered hands-on training in AtlantECO protocols and fostered new international research partnerships grounded in local ecological priorities.

Another notable example is the South Atlantic Ocean Sampling Day (SA-OSD) initiative: https://sites.google.com/view/sa-osd/english), a continent-wide collaborative effort to study the coastal marine microbiome using synchronized sampling with standardized protocols. The SA-OSD derived from the global Ocean Sampling Day initiative, which was a successful initiative in the northern hemisphere but had very few sites in the global south [19]. Since then, SA-OSD expanded this effort to over 25 locations across the South American bringing together research groups from Brazil, Argentina, Uruguay, Colombia, and Chile under a coordinated hub-and-node model. Participating institutions receive training and access to low-cost sampling kits, enabling molecular studies in areas where such tools were previously unavailable. This has allowed early-career researchers and students across the continent to gain hands-on training with cutting-edge protocols and engage in high-impact international collaborations. Beyond scientific outcomes, SA-OSD has fostered durable research networks and promoted ocean

Fig. 3 The Tara schooner's route in the Southern Hemisphere during AtlantECO's Mission Microbiomes, with sampling points marked in orange. Young researchers and students from Southern countries joined various legs of the expedition. A hands-on summer school took place in South Africa, both onboard the schooner and in the laboratories of the University of Pretoria

literacy by engaging local schools and communities in outreach events during sampling campaigns.

Another good example of south-south collaboration is the Microsudaqua network (https://microsudaqua.netlify.app/en/), where a group of South American aquatic microbial ecologists promote collective work and consolidate a collaborative space for the promotion of aquatic microbial ecology in the region. The network currently includes more than 80 researchers actively participating from six South American countries. Microsudaqua has successfully fostered regional integration through regular scientific meetings, joint research proposals, co-authored publications [20–23], standardizing protocols and training courses aimed at strengthening technical capacity in molecular and ecological methods. The network has played a vital role in empowering researchers, supporting early-career scientists, and enhancing visibility of aquatic microbial ecology produced in Latin America.

Looking ahead, scientific societies could play a stronger role in promoting equitable collaborations by supporting initiatives led by researchers from low- and middle-income countries. For example, providing targeted funding for low- and middle-income countries researchers to organize international conferences, workshops, and training courses within their home regions would help foster local leadership, build lasting research networks, and enhance the visibility of southern expertise. Hosting more scientific meetings in low- and middle-income countries would also create opportunities for early-career researchers to present their work, access international collaborations, and strengthen regional scientific communities.

Challenges

The success of such initiatives requires an exceptional effort to overcome structural barriers, particularly from the perspective of the global south. These include logistical and legal difficulties in conducting international sampling campaigns, financial constraints related to infrastructure and sequencing, inequalities in scientific publishing, and the systemic absence or underrepresentation of institutions from low- and middle-income countries in international science-policy frameworks. In this section, we detail these challenges, with the aim to provide a clearer understanding of the obstacles that must be

addressed to make inclusive and sustained ocean microbiome research the norm rather than the exception.

Securing sampling permits for foreign research vessels operating within another country's Exclusive Economic Zone (EEZ) is a highly complex and often protracted process. It typically involves coordination with national defense authorities, compliance with international agreements such as the Nagoya Protocol, and other bureaucratic challenges related to the importation of scientific equipment, customs clearance, and instrument calibration. These administrative and regulatory obstacles pose major barriers to the implementation of multinational oceanographic initiatives, frequently rendering such efforts exceedingly difficult to execute.

In AtlantECO, 10% of AtlantECO's total budget (50% of sequencing budget) was allocated to southern sequencing centers, specifically in the countries where the samples were collected, to leverage local sequencing facilities. Genoscope, the French national sequencing facility with extensive experience from the previous Tara Oceans project, shared all the protocols and the know-how with the sequencing facilities in the south to ensure methodological consistency and protocol standardization across sites, which was one of the key strengths of the Tara Oceans initiative. Nevertheless, sequencing costs remain significantly higher in many low- and middle-income countries due to import taxes and limited infrastructure. These economic barriers hinder the decentralization of sample analysis, as conducting sequencing in the global north remains significantly cheaper, creating challenges to effectively build and leverage local sequencing capabilities in the global south.

High article processing charges (APCs) for open-access publications disproportionately affect researchers in low- and middle-income contexts, where funding for publication is often limited. Most prestigious journals require APCs, which can range from hundreds to thousands of dollars per article, to make research freely available to the public. However, researchers in the global south, where funding is already limited, often cannot afford these fees, placing them at a disadvantage in sharing their findings. Without waivers or funding support, this pay-to-publish model limits the visibility and impact of southern-led research on a global scale. Some major publishers provide full APC waivers for papers whose corresponding authors are based in countries classified as low-income economies. However, this applies to only 26 out of the 217 countries currently listed in this category by the World Bank (https://datahelpdesk.worldbank.org/knowledgebase/articles/906519). Even with partial waivers of up to 50% offered by certain publishers to corresponding authors from lower-middle-income economies (approximately 51 countries), this policy remains inherently unfair, effectively barring most researchers from these regions from submitting their manuscripts to high-impact journals. The lack of affordable publishing options further exacerbates existing inequalities and restricts the participation of southern scientists in the broader scientific discourse [20].

In the field of ocean policy interfacing with science, there is also a critical need for greater involvement from southern experts and organizations. Low participation of southern countries in major international frameworks, such as the United Nations Convention on Biological Diversity (UNCBD), the United Nations Framework Convention on Climate Change (UNFCCC), and the High Seas Biodiversity Beyond National Jurisdiction (BBNJ) agreement, have been observed. These are the main frameworks for the development for sustainable ocean policies and practices, yet southern contributions to these discussions remain limited. This lack of low- and middle-income countries representation can restrict the diversity of perspectives and weaken the development of inclusive, globally beneficial policies. Increasing southern engagement in these platforms is crucial to ensure that the unique challenges and priorities of the global south are considered in international decision-making instances.

Organizing international regional research networks in most Southern regions is still a major challenge. Simple but essential tasks such as transferring funds from one country to another for organizing a workshop, for example, often become major obstacles. Moreover, local funding for such initiatives is scarce. There are very few meaningful agreements to facilitate south-south scientific networking. Southern countries typically fund stays abroad in the North. One notable exception is the *Asociación de Universidades Grupo Montevideo* (AUGM), a regional network that brings together some public universities from Argentina, Bolivia, Brazil, Chile, Paraguay, and Uruguay, to promote academic integration through mobility programs for faculty and students within the region. However, its reach remains constrained by the restricted number of institutions, limited funding and administrative complexity.

Research co-funding by southern countries is also uncommon and often not well understood by policymakers or even reviewers. In many countries of the global south, there is still no strong culture of co-funding scientific projects, particularly in the context of international collaborations. For example, when projects are approved by large international funding agencies such as the European Union, there is often a misconception among southern funding bodies that no additional support is necessary. It is commonly questioned why national resources should be allocated to initiatives that are already perceived as fully funded from external sources, and in some cases, regulations even prohibit the

allocation of national funds to projects that have already secured international financing. However, in reality, many international grants only partially cover research activities, and national co-funding remains crucial to enable full participation, including support for fieldwork, infrastructure, training, and capacity building at local institutions. This misunderstanding often results in a lack of co-investment, weakening opportunities for balanced and truly collaborative research partnerships. The absence of a co-funding culture thus limits the ability of southern institutions to engage on an equal footing with northern partners, reinforcing asymmetries in collaborations and undermining efforts toward more equitable and sustainable scientific partnerships. Addressing this gap will require building greater awareness among policymakers and funding agencies about the actual structure and needs of international scientific collaborations.

Also, funders from southern countries should be encouraged to invest more in south-south collaborations, which will require raising funders' awareness of the scientific and societal value of regional collaboration, integrating south-south cooperation into national science priorities, establishing dedicated funding mechanisms, promoting bilateral and multilateral co-funding agreements, and leveraging regional organizations as intermediaries to facilitate and coordinate initiatives.

Finally, addressing the disparities in resource and infrastructure distribution remains a significant challenge. Oceanographic research is costly, and microbiome studies are consequently inaccessible in many regions of the global south. Research vessels, essential for sampling in marine microbiology, are scarce and expensive to operate and maintain, which restricts sampling activities predominantly to countries or institutions with robust funding. Additionally, the limited availability of regional networks among researchers exacerbates the problem, leading to inefficient scheduling and underutilization of existing vessels.

In countries of continental scale, such as Brazil, these challenges become even more pronounced due to uneven regional development. For instance, while well-equipped research centers with advanced sequencing platforms and oceanographic equipment exist in the southeastern and southern regions of Brazil, large portions of the country, particularly in the northern and northeastern coastal zones, often lack even basic laboratory infrastructure and technical expertise.

Similar disparities occur in Africa, where South Africa possesses relatively advanced oceanographic research infrastructure and trained personnel, while neighboring countries such as Namibia, Angola, Democratic Republic of the Congo, Senegal and many other countries struggle with severely limited research capabilities, inadequate infrastructure, and insufficient technical training. Such stark disparities not only hinder comprehensive research coverage but also perpetuate regional inequalities in scientific capacity, ultimately limiting the scope and impact of national and international collaborative efforts in ocean microbiome science.

Concluding remarks

Research on the ocean microbiome is advancing rapidly, yet most of this research has been concentrated in a relatively small group of high-income countries, despite the southern hemisphere encompassing much of the world's oceans. The disparities in sampling efforts, access to technology, and human resources between the high-income and low- and middle-income countries highlight the urgent need for more inclusive and equitable research practices.

We presented here some cases of successful north–south and south-south collaboration. Such initiatives demonstrate the value of involving local researchers in shaping research priorities and planning scientific missions in a bottom-up fashion, leading to mutually beneficial outcomes and fostering long-term partnerships. They underscore the importance of ethical engagement and equitable practices in scientific research, moving away from the outdated and problematic parachute science model.

However, significant challenges remain. The complex logistics of international research, including bureaucratic hurdles, high costs, and disparities in infrastructure, continue to impede progress. To address these issues, it is crucial to:

- Address resource and sampling gaps: Invest in infrastructure, technology, regional research networks, and training programs in the global south to reduce disparities and enhance local research capabilities. Such investments, preferably co-funded by both northern and southern partners, should prioritize not only the sampling of vast, unexplored areas in the south but also the capacity to maintain, process, and analyze these samples locally. This includes improving access to advanced sequencing facilities, training for data analysis, and reducing associated research costs, ultimately fostering a more equitable research environment that empowers local scientists and addresses critical knowledge gaps.

- Promote ethical research practices and support equitable collaborations: Strengthen north–south and south-south collaborations by ensuring fair participation and shared benefits, particularly by involving local researchers in defining and leading research agendas to combat parachute research by fostering partnerships that are respectful, inclusive, and collaborative from the outset. The adoption of structural mechanisms such as reflexivity statements can enhance transparency, accountability,

and the ethical integrity of international collaborations, helping to move beyond parachute science.

- Strengthening both north–south and south-south cooperation is crucial for sustainable capacity building. Establishing a robust culture of co-funding, facilitating inter-regional mobility, and overcoming administrative barriers are key to fostering autonomous and sustainable research environments. Scientific societies, funding agencies, and international organizations must actively support initiatives that empower researchers from the global south to coordinate, lead, and expand regional research networks.

Beyond the responsibility of researchers themselves, achieving equitable and inclusive ocean microbiome research requires the active engagement of multiple stakeholders. Funders play a pivotal role by designing grant programs that incentivize north–south and south-south collaborations, require equitable participation, and provide support for capacity building in underrepresented regions. Research institutions, particularly in high-income countries, must value and reward equitable international collaborations as part of performance evaluations, recognizing that such efforts are often more time- and resource-intensive than traditional metrics reflect. Governments should prioritize bilateral and multilateral agreements that facilitate scientific exchange, simplify legal frameworks for resource sharing, and co-invest in international initiatives. Building alignment across these sectors is crucial to dismantling systemic barriers and fostering a truly global, inclusive marine science community.

By addressing these challenges and fostering inclusive collaborations, the scientific community can ensure that ocean microbiome research benefits all regions equally, contributing to a more comprehensive understanding and sustainable management of our global ocean. Recognizing the ocean as a global common, it is crucial that both high-income and low- and middle-income nations share responsibility for its stewardship, ensuring that research and conservation efforts reflect the needs and knowledge of all regions. This approach will lead to more equitable and effective solutions for the future of our oceans and ultimately for humanity.

Supplementary Information

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Supplementary Material 1.

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Authors' contributions

H.S. participated in all aspects of the study, including conceptualization, methodology, investigation, data curation, writing, and project administration. P.H. and C.D.S.-J. contributed to data analysis, figure preparation, and manuscript review. All authors provided critical feedback, manuscript review, corrections, and contributed to the broader context and collaborative framework of this work. All authors reviewed and approved the final manuscript.

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Data availability

Not applicable.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

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