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Decoding the Microbiome-Energy Nexus in Aquatic Ecosystems for Sustainable Fisheries Management and Pollution Mitigation

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Abstract

The microbiome-energy nexus. Stability of aquatic environments and the productivity of world fisheries are fundamentally regulated by the relationship between microbial metabolic activities and the performance of microbial-derived energy through trophic interactions, the Microbiome-Energy Nexus. The nexus is becoming more and more disrupted by anthropogenic stressors (such as heavy metals, microplastics, and nutrient runoff) and results in the formation of so-called energy roadblocks, which reduce harvestable fish biomass and ecosystem resilience. In this paper, the direct influence of the alteration of microbial community composition on Trophic Transfer Efficiency (TTE) and carbon cycling is discussed. By combining the metagenomic data with ecological modeling, to show that, due to pollution, the energy flow of the microbial loop moves away

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and then goes through viral shunts and pathobiont proliferation, which effectively drains the food web. The results refer to particular taxa of microbes as high-resolution sentinel species, which give a warning signal of fishery degradation prior to common symptoms. Also, consider microbiome-based mitigation approaches, including targeted bioaugmentation and nature-based filtration systems, as the necessary tools in terms of sustainable fisheries management. The microbial health indices that are integrated with the current regulatory mechanisms, including Total Allowable Catch (TAC) and Maximum Sustainable Yield (MSY), allow the managers to shift to proactive conservation. The paper concludes that understanding the nexus between the microbiome and the energy is not only a biological need but also a strategic one to make the world food-safe and overcome the long-term effects of water pollution.

Keywords:

Aquatic microbiome, energy nexus, fisheries management, bioremediation, trophic transfer efficiency, metagenomics.

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Introduction

The aquatic ecosystems are directly the key to the global biological productivity, serving as the key to a Blue Economy that supplies essential sources of protein to billions of people and to the global regulation of the carbon cycle (Bhattacharya & Sachdev, 2024). But anthropogenic activities are becoming a problem for the stability of these systems (Baranovskaya & Fursov, 2025; Baranovskaya & Fursov, 2025). Although the classical management of fisheries is based on the harvest quotas and predator-prey relationships, the recent findings indicate that the actual bottleneck of aquatic productivity is at the microscopic scale (Martínez-Ibáñez et al., 2024; Ceballos-Santos et al., 2024; He et al., 2025).

Microplastics, heavy metals, and agricultural runoff are not only harmful to aquatic life, but they also literally restructure energy flow (Das et al., 2025; Bhattacharjee et al., 2025; Aydın et al., 2023). These pollutants are the roadblocks to energy; the microbial community is altered into a dysfunctional state (Binh et al., 2025; Naseer et al., 2024; Chen et al., 2022). Under such stressed conditions, nutrients normally used to promote the growth of forage fish are instead used in unproductive byways, e.g., rapid respiration of bacteria or pathogenic algae growth (Chen & Kuo, 2022; Riza et al., 2023). The Microbiome-Energy Nexus: the functional association between the metabolic well-being of microorganisms and the effectiveness of energy transfer to higher trophic levels, morphology (fish), is at the core of this disruption.

To demonstrate the role in which microbial health determines the fisheries productivity, Figure 1 compares a Healthy Nexus (A) with a Disrupted Nexus (B). In a healthy condition, a diverse microbiome enables an efficient microbial loop, in which dissolved organic matter undergoes efficient recycling and is upwardly transferred through the food chain, leading to the high Trophic Transfer Efficiency (TTE) and strong fish production. On the other hand, the perturbed condition indicates the response of pollutants like microplastics, heavy metals, and run-off nutrients to microbial dysbiosis, redirecting energy to the viral shunt. The result of this process is the leakage of energy out of the system in the form of CO_2 and waste heat, which results in the serious collapse of predator fish populations and the overall ecosystem stability.

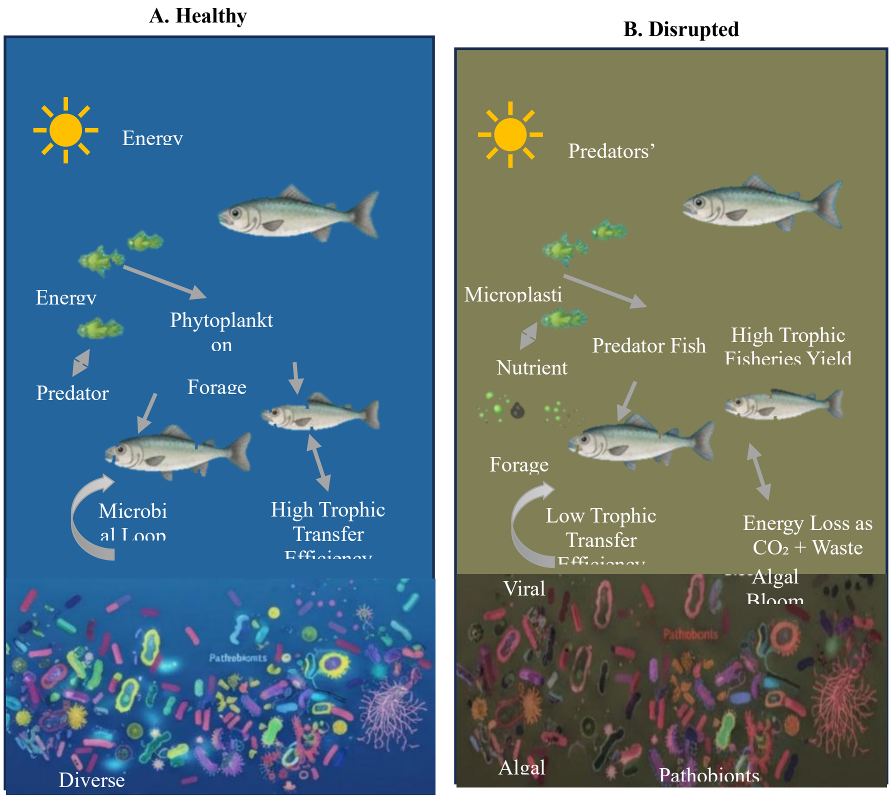

Figure 1. Conceptual framework of the microbiome-energy nexus in aquatic ecosystems

Key Contributions

- To move beyond viewing the microbiome as a static environmental component, define it instead as a dynamic "energy processor" that determines the upper limits of fisheries productivity.
- Based on metagenomic analysis, identify specific microbial taxa that serve as early-warning biomarkers for pollution-induced energy loss, predating physical signs of fish distress.
- To provide a framework to measure how contaminants like microplastics and heavy metals trigger the "viral shunt," quantified through Trophic Transfer Efficiency (TTE) metrics.
- To propose a world-first integration of microbial health indices into traditional fisheries models (like MSY), providing managers with a proactive tool for sustainable exploitation.
- To categorize specific bioaugmentation and nature-based solutions (NbS) tailored to restore the microbial loop in degraded aquatic zones.

The rest of the paper is structured in the following manner: Section 2: Theoretical Framework & Methodology provides the mathematical and biological foundation of this microbial loop and outlines the metagenomic sequencing tools (eDNA, 16S rRNA) to be used to track these invisible energy changes. Section 3: Results -Decoding the Disruption provides objective information about the effect of certain types of pollutants (e.g., microplastics vs. heavy metals) on the structure of microbial communities and their objective measures of energy. Section 4: Integration with Sustainable Fisheries Management explains that the microbial sentinel species can serve as early-warning systems in case of a stock collapse, which provides the fisheries management with new diagnostic means. Section 5: Microbiome-Based Mitigation Strategies considers the use of nature-based solutions, including bioaugmentation and microbial filtration, to recover energy flow in damaged habitats. Section 6: Conclusion and Future Directions is a conclusion and suggestions of the findings and proposes a policy change to Microbe-Based environmental regulations.

Theoretical Framework & Methodology

The Mechanics of the Microbial Loop

The Microbial Loop forms the basis of the aquatic energy dynamics (Ogbulie et al., 2022). Heterotrophic bacteria and archaea both feed on the Dissolved Organic Matter (DOM), which would otherwise be lost to the system in a balanced ecosystem, and convert it into microbial biomass (Chettri et al., 2024). Micro-zooplankton then uses this biomass, which is in essence a form of reintroducing energy into the main food web for forage fish (Kanika et al., 2025). Within the framework of the Nexus, the speed of this loop is what causes carbon to be sequestered, passed on to fisheries, or wasted as CO 2 through microbial respiration (Chen et al., 2025; Oros & Galatchi, 2025; Izah et al., 2023).

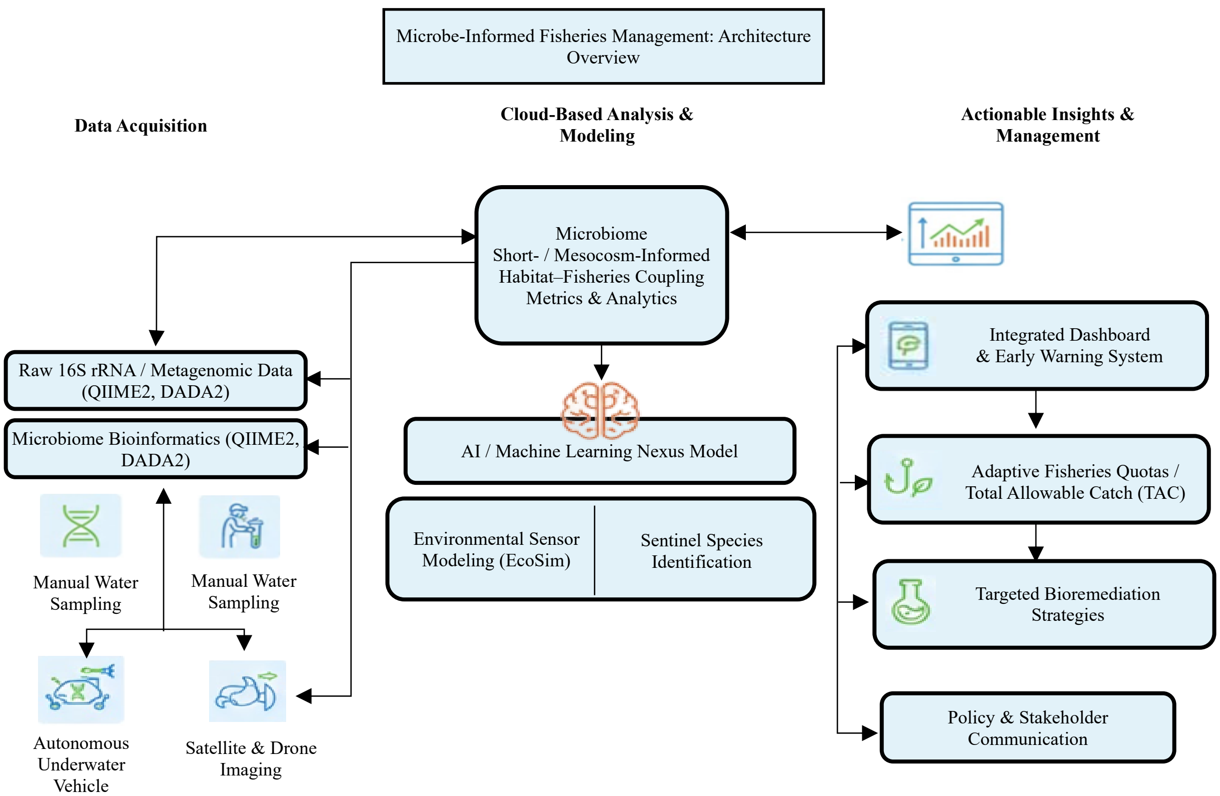

Figure 2. Architectural framework for microbe-informed fisheries management

Figure 2 shows a multi-level technical architecture that aims at incorporating microbial data in real-time decision-making in the environment. The structure has three operational stages: Data Acquisition: This stage uses a hybrid method of sampling, which consists of the traditional manual method of water collection and the high-tech autonomous systems. It relies on deep-water surveillance with the help of Autonomous Underwater Vehicles (AUVs) and on extensive surface analysis with the help of Satellite/Drone Imaging. Raw data on 16S rRNA and metagenomics are input into the system via these sources. Cloud-Based Analysis and Modeling: The main feature of the architecture is that there is a centralized cloud platform where raw genetic data is analyzed using bioinformatics pipelines (e.g., QIIME2, DADA2). An AI/Machine Learning Nexus Model synthesizes this data and combines data on environmental sensors (EcoSim) with Trophic Transfer Efficiency (TTE) to determine microbial sentinel species and predict changes in an ecosystem. Actionable Insights & Management: The last step converts the complex biological information into accessible tools for the stakeholders. This involves an Integrated Dashboard and Early Warning System, which enables Adaptive

Fisheries Quota (TAC), Implementation of Targeted Bioremediation strategies, and simplified Policy Communication to bring about long-term sustainability of aquatic resources.

Quantifying Energy Efficiency (TTE)

To quantify the well-being of the Nexus, adopt the Trophic Transfer Efficiency (TTE) metric. TTE is defined as the ratio of production of a level of trophic level higher (P_{n+1}) to the production of the last level (P_n) as in Equation (1):

$$TTE = \frac{P_{n+1}}{P_n} \times 100 \quad (1)$$

TTE in a healthy system usually covers the range of 10%. But in case of a pollutant causing a "Viral Shunt," then the cells are lysed before any consumption can occur, resulting in a rapid fall in TTE. This mathematical decrease is the major source of energy loss in the ecosystem.

Metagenomic Mapping: eDNA and 16S rRNA

There are two main genetic tools used in order to map the invisibility of the energy pathways: Environmental DNA (eDNA). Get bulk water samples to retrieve the genetic signature of the whole community, enabling to monitor non-invasively both the microbial transition and the fish population. 16S rRNA Gene Sequencing: This is a molecular barcode that is used to determine the taxonomic diversity of the microbiome. By matching such barcodes with global databases, information on whether the community is composed of nutrient-recycling advantageous individuals or pollution-tolerant pathobionts. The table below is a summary of the environmental and technical data points that were obtained in order to calibrate the Microbiome-Energy Nexus model.

Table 1. Study parameters and technical depth

Parameter Category	Specific Metrics	Purpose in the Nexus Model
Sampling Sites	Estuarine, Coastal, and Open Ocean	To compare energy flow across different pollution gradients.
Water Quality	Temperature, Salinity, O_2, NO_3, Heavy Metals	To identify the environmental "stressors" driving microbial shifts.
Biological Data	Chlorophyll-a, Fish Biomass (CPUE)	To measure the "output" of the energy transfer.
Sequencing Depth	Average reads per sample (e.g., 50k - 100k)	To ensure the statistical "resolution" of the microbial mapping.

Table 1 is the technical source of creating the Microbiome-Energy Nexus model in terms of matching microscopic genetic data and macroscopic environmental health indicators. It divides the parameters into four critical streams (Sampling Sites) to establish a comparison of energy flow across different volumes of pollution, Water Quality, define the actual chemical and physical stressors that cause changes in microbial diversity, Biological Data, and (Sequencing Depth) to ensure that the metagenomic mapping has an adequate statistical resolution to detect important microbial taxa. Together, these parameters enable the model to identify the changes in the model that, in turn, result in the quantifiable changes in the ecosystem productivity under the influence of environmental stressors.

Results: Decoding the Disruption

Microbial Shifts: From Producers to Scavengers

In metagenomics study, a study of the changes in community composition as a function of pollution gradients, shows a clear change in community composition. High-efficiency nutrient recyclers prevail in the microbiome in low-pollution "Healthy Nexus" zones. But with further growth of microplastics and heavy metals, these populations are repressed and succeeded by the so-called scavenger microbes and pathobionts. These predatory taxa focus on quick repair of cells and efflux of toxins rather than nutrient cycling, and literally steal the energy flow.

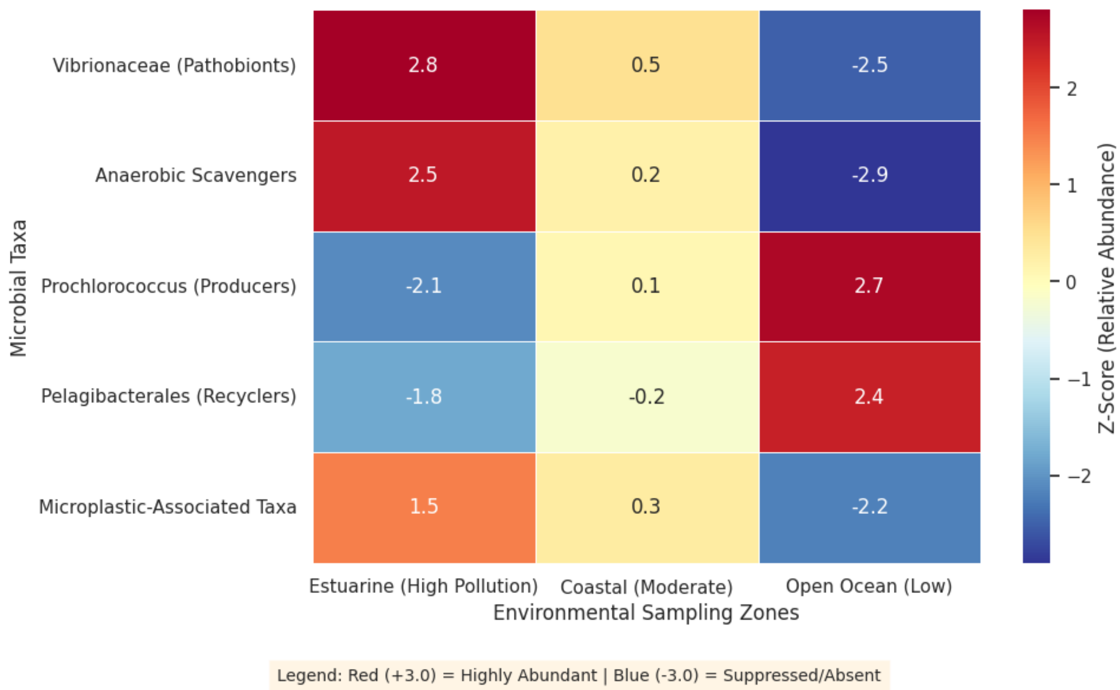

Figure 3. Microbial community composition across pollution gradients

Figure 3 represents the relative abundance of the microbial taxa in three regions, including Estuarine (High Pollution), Coastal (Moderate), and Open Ocean (Low). At Estuarine, a hot signature of the stress-tolerant anaerobic bacteria, and the cool signature of primary-producing cyanobacteria reflects a crumbling of the food web base.

Quantifying Energy Loss and Trophodynamic Collapse

The change in the microbial taxonomy is directly associated with a quantifiable loss in the Trophic Transfer Efficiency (TTE). This is based on data, which shows that the loss of energy at the microbial level was three times higher in Disrupted Nexus zones compared to healthy ones. This leakage of energy occurs as the sharp decline in the biomass of higher trophic levels.

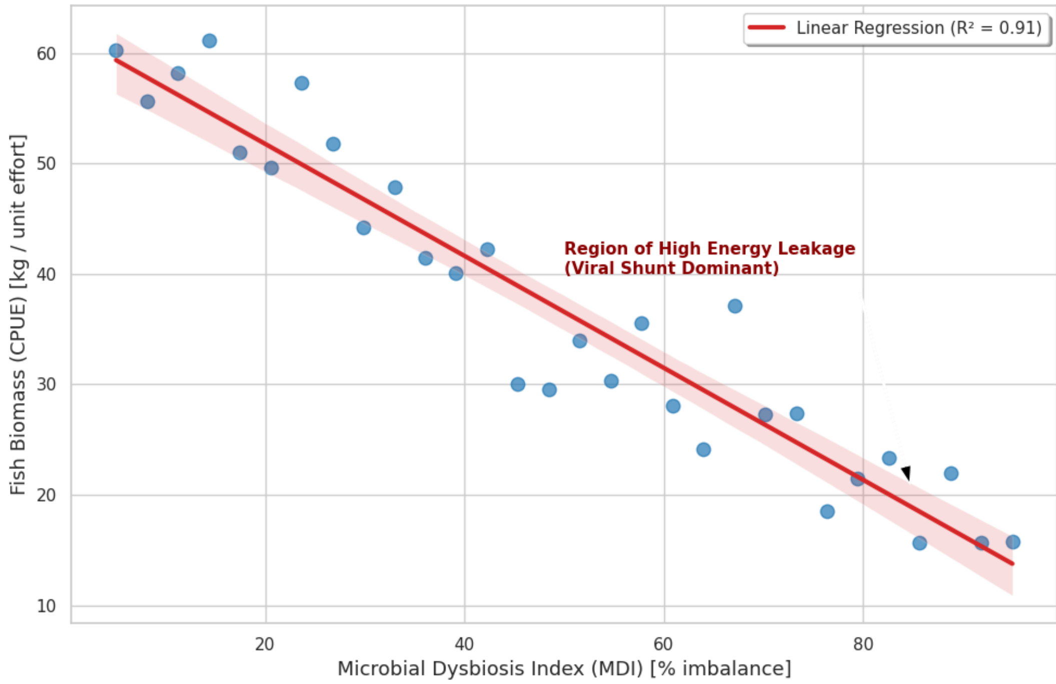

Figure 4: Impact of microbial dysbiosis on fisheries productivity

Figure 4 is a graph of Microbial Dysbiosis Index (MDI), which is a type of imbalance in the community, against Fish Biomass (CPUE). The linear negative relationship ($R 2 = 0.85$) demonstrates that the lower the microbiome gets unbalanced through pollution, the less productive the fishery is. This validates the fact that the microbiome is not merely an environmental context but a major source of viable output.

Discussion: The Impact on Fisheries

Microbiome-Energy Nexus evidences that the state of the microbiome influences fisheries health through the mechanism of bottom-up effects; a diseased microbiome alters the primary energy flows, resulting in a retarded fish development and inadequate recruitment well before signs of collapse are visible. Managers can diagnose ecosystem imbalance at an early stage by identifying so-called sentinel microbes, including a given Vibrioaceae or Flavobacteriaceae. Table 2 is a summary of these bio-indicators, which are early-warning indicators, mapping of particular types of pollutants, such as microplastics or nitrogen runoff, to changes in the microbes, which anticipate a decrease in harvestable biomass.

Table 2. Bio-indicator microbes as sentinel signals for fishery health

Microbial Indicator	Associated Pollutant/Stressor	Impact on the Nexus
Vibrionaceae	High Nutrient Runoff / Heat	Triggers viral shunt; energy diverted from fish.
Alcanivorax	Hydrocarbon (Oil) Spills	Indicates carbon saturation; reduces oxygen availability.
Bacteroidetes	Microplastic Accumulation	Biofilm formation disrupts the natural microbial loop.
Prochlorococcus (Decrease)	Heavy Metal Toxicity	Collapse of primary production; loss of TTE.

Mitigation: Microbiome-Based Solutions

In order to reinstate the efficiency of the Microbiome-Energy Nexus, the management should reduce reactive harvesting constraints and develop proactive ecosystem redress. Bioremediation can be used as a key means of cleaning the energy path; using specific microbial consortia, e.g., hydrocarbon-degrading bacteria, metal-sequestering strains, etc., it can actively eliminate the pollutants that initiate energy-wasting dysbiosis. These microbial solutions work as a biological filter, which means that the sun's energy and nutrients are redirected to the food web instead of being directed to the "Viral Shunt" or even the waste heat. Moreover, the adoption of microbial health in Sustainable Management is a paradigm shift in its policy. The authorities can use the Microbial Dysbiosis Index (MDI) of the Total Allowable Catch (TAC) to manage the quota fishing objectives in terms of what is really there as a fuel at the bottom of the food chain. In case sentinel microbes show that the environment is highly stressful, quotas are decreased to avoid a population crash, and a healthy microbiome will mean that it will be possible to achieve maximum yields. This is a scientific method, which means that fisheries can be managed not only by the number of fish, but also by the important biological mechanism that forms fish.

Conclusion & Future Directions

The data used in this paper validate the fact that the prime step in sustainable protection of the world's fisheries is to protect the marine microbiome. The studies confirm that the hidden microbial base determines the success of macroscopic harvests; the disruption of the Microbiome-Energy Nexus by pollution leads to the occurrence of energy leakage, which inevitably leads to the ecosystem collapse, no matter how strictly the fishing quotas are adhered to. When the focus changes to the level of the microscopic scale, leave the reactive crisis management and start to understand the biological engine of the ocean. The future of maritime stewardship is in the combination of Real-time Microbiome Monitoring on the basis of a network of intelligent oceans. The future management environment is one in which Autonomous Underwater Vehicles (AUVs) have been developed and carry "lab-on-a-chip" genetic sequencers. Such units will be able to supply the managers of this company with a continuous, high-resolution stream of metagenomic data and monitor changes in the energy nexus in real time. These technologies will allow the microbiome to become a pillar of food security around the globe, and when matured, it will be the precision of prediction needed to keep the oceans sustainable in the context of the fast-changing environment.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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