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GETTING BY ANTHROPOCENE WITH A LITTLE HELP FROM MICROBES

Passando pelo Antropoceno com uma pequena ajuda dos micróbios

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ABSTRACT

When modern man evolved in Africa 250,000 years ago by hunting and gathering, would he dream of megalopolis and flying machines? Would he ever understand how we managed to create and expand so much that this could cause our very decline like an Icarus that reached for the sun while the wax on his wings melts? Nowadays, as we find more and more evidence of the negative impacts we have caused to the biosphere, we are also looking for solutions to write a different future, a sustainable future. In this perspective, I present how a microbcentric approach can help achieve many of the Sustainable Development Goals (SDGs) based on the knowledge that microorganisms are the engines of life on Earth. The science of microbiology has shown that most microorganisms are not pathogens but live in close association with almost any plant or animal, with many advantages that can certainly be used in an evidence-based manner. Each of the 17 SDGs can be strengthened by considering microbes – from improving or restoring soil fertility to produce food to protecting blue carbon ecosystems, such as corals and mangroves. Recognizing that these minuscule beings hold one of the keys to a sustainable future is essential, which would be achieved by strengthening research, microbial literacy actions, and cooperation among scientists, stakeholders, decision-makers, and society. Microorganisms can help us create opportunities for the future, like a Daedalus that finally gets heard by an arrogant Icarus.

Keywords: Sustainable Development Goals, bioeconomy, microbial innovations, sustainability, climate change.

RESUMO

Quando o homem moderno evoluiu na África há 250 mil anos como caçador-coletor, sonharia ele com megacidades e máquinas voadoras? Será que ele entenderia como nós conseguimos criar e expandir de forma tão intensa que isso poderia causar o nosso próprio declínio, como um Ícaro que atinge o Sol enquanto a cera de suas asas derrete? Atualmente, conforme encontramos mais e mais evidências dos impactos negativos que causamos à biosfera, também buscamos por soluções para escrever um futuro diferente, um futuro sustentável. Nessa perspectiva, eu apresento como uma abordagem microbicêntrica (centrada nos micro-organismos) pode ajudar a atingir muitos dos Objetivos de Desenvolvimento Sustentável (ODS) com base no conhecimento de que os micro-organismos são os motores da vida na Terra. A ciência da microbiologia mostrou que a maioria dos micro-organismos não é patogênica, mas vive em associação próxima com quase qualquer planta ou animal, com muitas vantagens que podem, certamente, ser utilizadas de modo baseado em evidências. Cada um dos 17 ODS pode ser fortalecido ao se considerar micro-organismos – desde melhorar ou restaurar a fertilidade do solo para produzir alimentos a proteger os ecossistemas ligados ao carbono azul, como corais e manguezais. Reconhecer que esses seres minúsculos possuem uma das chaves para um futuro sustentável é essencial, o que pode ser atingido pelo fortalecimento da pesquisa, ações de letramento ou alfabetização microbiana e cooperação entre cientistas e outros atores, como tomadores de decisões e sociedade. Os micro-organismos podem nos ajudar a criar oportunidades para o futuro, como um Dédalo que finalmente é ouvido por um arrogante Ícaro.

Palavras-chave: *Objetivos de Desenvolvimento Sustentável, bioeconomia, inovações microbianas, sustentabilidade, mudanças climáticas.*

INTRODUCTION

Back in 1992, when the United Nations Conference on Environment and Development (the "Earth Summit", in Brazil also known as "Eco92") was held in Rio de Janeiro, I was a seven-year-old child. Thus, I consider myself an optimist from "Eco92 generation". This means that I have grown up believing that there was hope for Earth's environmental conservation, that Sustainable development was possible, and, most of all, that we, as a conscious species (*Homo sapiens sapiens*), held the key for a holistic future. In this utopic future, we would embrace our responsibilities raised by our own so especially convoluted cerebrum. Nowadays, as a researcher, I am really worried about the paths our large frontal lobes had paved for our future.

I once read that one of the most common reactions of officers arriving in Europe after the end of the World War II was desolation; desolation for an entire devastated continent where once beautiful and proud cities used to stand, now scorched and deconstructed. I could only imagine that maybe Thomas Goreau would feel be same if he could dive in Discovery Bay (Jamaica) nowadays. For me, this very visual comparison resumes the extent to which our oceans are disturbed, fighting a war of global dimensions.

Nevertheless, the ocean, especially the deep ocean, was once considered the last frontier. Now it is explored at a very fast pace of change. Halpern *et al.* (2019) reported that over 85% of the 220 coastal countries and territories experienced average increasing rates of cumulative human impacts. The fastest increases occurred in parts of the Black Sea, tropical Atlantic Ocean, temperate Northwest Pacific Ocean, and sub-tropical Indian, Atlantic, and Pacific Oceans, which evidences the wide geographic range of such impacts. In fact, those regions are at high risk of ecosystem collapse. The greatest changes were experienced in the Caribbean and mid-latitudes of the Indian Ocean (Halpern *et al.*, 2019).

This faster pace of impacts that cumulates on the oceans have its origin in a multitude of claims over the maritime resources; claims which are not new, but whose intensity, extent, and diversity have profoundly changed the relationship between humanity and the oceans. Jouffray and colleagues (2020) have named this unprecedented race for ocean food, material, and space as the "Blue Acceleration" – a new phase in maritime expansion in which the ocean is not only crucial for sustaining global development trajectories but is also profoundly changed in the process. As a result, our once wild, strong, and vital oceans were changed in civilized, many times brutalized, environment as the human expansion to the sea accelerated.

Using again the war analogy, history has shown many examples that during the many wars human beings have been involved throughout their history, it is the subjects living in territories at war who suffer the most. If we consider our oceans a territory at war, what place is reserved for other species that share the oceans with us? What place is reserved for human populations that depend on that warlike territory to survive? As if we were living in a war, today we experience the demise of oceans' biodiversity, with fires being shot by too many stressors at the same time. Evolution, paleontology, and archeology sciences have revealed that, from the beginning, life has passed by many challenges, from volcanos eruptions and oxygen intoxication to glacial eras, earthquakes, and even meteorites. Nevertheless, it is our very way of life, constructed over the years – from the quest for fire to the green revolution, world wars, and pandemics – that is now the biggest threat.

In the meanwhile, while oceans enter in a vertiginous decline, global countries continue to claim more and more maritime territories as sovereignty rights. Nonetheless, as proposed by Achille Mbembe's concept of necropolitics, the power of sovereignty is now played by dictating who may live and who must die. This logic applies also in this context as the countries pursue maritime territories to explore their resources ("who may live"). When doing this, they mostly ignore environmental liabilities and treat the negative impacts on the biosphere as negative externalities ("who must die"). In this power struggle, little power is given to life. Mbembe's political perspective is closely applied to the environmental crises we are facing nowadays.

Still, Earth, in its tireless and eternal transformation, as quoted by Rossi (2019), will continue its geological evolution as it has made after the five mass extinctions scientists have managed to document. Now, with this in mind, what can we do? Close our arms and expect for the end (our very end)? What about generations to come? Is it fair to make them inherit this dystopic world? As present generations, we must be able to construct a sustainable future. As scientists, we have the keys to provide solutions.

Back in 2016, the first World Assessment of the United Nations stated that humanity was running out of time to reverse the decline of oceans health and build a sustainable ocean. With the conviction that this opportunity still exists, in 2017, the United Nations launched the Decade of Ocean Science for Sustainable Development, with a duration from

2021 to 2030. To reach this objective, they had put ocean science in the center of this process, covering natural and social disciplines related to the ocean to ignite a paradigm shift in the generation of qualitative and quantitative ocean knowledge for the science we need to fight the crises we face (IOC/Unesco, 2021).

This science we need, along with technology and innovation, is key to the construction of the 2030 Agenda. Microbiology stands out in this context by offering insightful knowledge on the microbial engines of Earth's biosphere as well as by being strongly related to our day-to-day living, although in an invisible way. Themes such as our health, emerging diseases, antimicrobial drug resistance, food security, environmental sustainability, bioremediation, environmentally friendly fuels, new drugs, and water quality are all related to the study of microscopic organisms, the unseen majority (Van Der Heijden; Bardgett & Van Straalen, 2008).

Considering such a challenging task and the vast evidence of the vital support microorganisms have given to the biosphere, in this perspective, I call attention to microbes and the power of a "microbcentric" (*sensu* Cavicchioli *et al.*, 2019) standpoint to approach Anthropocene's challenges. Based on the incorporation of the knowledge on this microbial unseen majority, this approach can not only improve our knowledge on how microorganisms affect and are affected by climate change but also how they can provide science-based solutions to improve planetary health and help to achieve many of the 17 Sustainable Development Goals (SDG).

Studying microbes helps to construct a timeless chronicle full of hints of how to construct a sustainable future

From villains to saviors, what we know about microorganisms' role in the biosphere has been going through many changes. This paradigm change, in which microorganisms went from only pathogens to our "last organ", has put microorganisms in a central role of a sustainable future. Indeed, if we took into consideration how life has appeared and evolved on our planet, we can envisage microorganisms as a permanent life unit that not only initiated life on Earth but also witnessed at least five mass extinctions. Nowadays, as we experience global climatic changes, microbes are expected to guide us through this dystopic reality we have managed to construct.

After the SARS-CoV-2 pandemic, microbiology became a topic in everyday conversations with family, colleagues, and neighbors, in the supermarket, on the news and on social media. The term microbiome is becoming a familiar concept to the general public through exploring the hidden microbial roles in nutrition and health, and promising results also boosted a new "microbiome market" (Berg *et al.*, 2020). In addition, the field has already delivered novel and important concepts with wide applications, such as the holobiont theory of evolution or the meta-organism concept (Rosenberg *et al.*, 2007), a fundamental paradigm shift. The microbiota is now considered an inseparable functional unit to be considered along with the complex meta-organisms with whom they share the symbiosis. Considering those meta-organisms as a united entity, it is easier to envisage a perspective that implies the interconnection of life through their respective microbiota as an alternative to our Anthropocene crisis. Microbiomes, through this perspective, can base green economy business, replace nitrogen fertilizers linked to dead zones, prevent infectious diseases, and improve crop production. There is a lot of power in such minuscule beings.

1. *Microorganisms alone have populated, dominated, and shaped our planet for over 3 billion years*

When plants and metazoan first emerged, about 800 million and 700 million years ago, respectively, microbes already existed for about 3 billion years (first evidence of life date back to 3.7 billion years). Their presence is so striking that even the cataclysmic "great oxidation event" (2.4 billion years ago) – i.e., the shift in the reduction-oxidation status of our planet – can be traced in the geologic record (Blaser *et al.*, 2016). Those oxygen releasers, organisms capable of oxygenic photosynthesis, were ancestors of today Cyanobacteria and were responsible for one of the most significant mass extinctions of Earth (Hodgskiss *et al.*, 2019). At the time, there were no animals and plants to be extinct yet. It was a world of microbes only. Modern humans would emerge only about 250,000 years ago.

However, with oxygen-coupled reactions as a source of energy significantly greater than previously anaerobic lifestyles, a rapid diversification of life took place – the archaean genetic expansion. This expansion led subsequently to the evolution of multicellular organisms and, ultimately, to the remaining tree of life (Blaser *et al.*, 2016). All those billion years of microscopic activities set the ground for life expansion. Since then, throughout geological time, microorganisms remained, some as living fossils of how our planet looked like in its early years.

Back in the seventieth century, Anton von Leeuwenhoek provided access to the invisible world of microbes while observing bacteria, fungi, and protozoa (called "animalcules") from mud, water, and dental plaque in his rudimentary microscopes. In its turn, Robert Koch created the concept of pathogenicity and explained the microbial origin of human and animal diseases. Since then, microorganisms' role was reduced to disease agents that needed to be eliminated. It was only at the end of the ninetieth century that the pioneering microbial ecology studies of Sergei Winogradsky, Martinus Beijerinck, and Lourens Baas Becking broke that paradigm. After that, we gained access to the vast world of microorganisms and could note that only a small proportion of them was indeed pathogenic. Since then, microbiologists established another paradigm: that microorganisms are everywhere mostly with beneficial effects, such as being the biogeochemical engines that support all life on Earth (Blaser *et al.*, 2016; Berg *et al.*, 2020).

The Sustainable Development Goals – how can microbes help?

The present scenario of Anthropocene can be summarized in two main points: (1) a huge environmental crisis that gets worse each day, and (2) the challenge to construct a sustainable future. How can we pursue such a task? Quoting UN ex-secretary Ban Ki-Moon "*We don't have a plan B, because there is no Planet B*". In this regard, the 17 Sustainable Development Goals (SDG) appear as the last effort for reaching sustainable economic development and a possible future. The SDGs are classified into five categories – People, Planet, Prosperity, Peace, and Partnerships – with the aim to develop the solutions to enable economic and societal development without environmental damage (Akinsemolu, 2018).

Taking into consideration the many positive services of microbiomes for humans, plants, animals, and the environment (to cite a few: resistance to pathogens, vitamin synthesis, fat regulation, nutrient absorption, soil fertility, feed conversion, protection from toxins, bioremediation, carbon sequestration, and biogeochemical cycles), microbiomes of soils, water bodies, oceans, plants, and animals are seen as one of the keys to environmental health. In this regard, they can also help to reach for the 17 SDG from the United Nations (Figure 1). As discussed above, microorganisms date back to the origin of life and will likely exist beyond any future extinction event. Thus, they are perfect tools to help us in this mission.

Considering how diverse and metabolic versatile microbes are, they are belittled in the operationalization of the SDGs. In order to argue in favor of considering and using microorganisms in this task, I will tell you some tales of the successful use of microorganisms in different challenges of humankind. They are exposed as reasons to base the claim that the power of microorganisms can help us to deal with ongoing and future challenges to reach for a sustainable future.

Figure 1 – How to reach for the 17 Sustainable Development Goals through a microbcentric approach

1. Oil eaters from Macondo

After the disastrous oil spill in the Macondo wellhead site at the Gulf of Mexico (*Deepwater Horizon* oil spill), in 2010, a massive response tried to protect beaches, wetlands, estuaries, and associated communities from the 780 million liters of oil discharged. The oil impacted coastal, continental shelf, open ocean, and deep benthic ecosystems (Schwing *et al.*, 2020). Then, the Gulf of Mexico Research Initiative (GoMRI) was established to provide resources for advancing the understanding of marine hydrocarbon microbiology, among other biological, physical, and chemical components related to the disaster. The Initiative was able to examine hydrocarbon-degrading microbes in unprecedented detail by using genomic and bioinformatics tools and gain insight into how microbes respond to hydrocarbon infusions. They discovered novel species, genes, metabolic pathways, and community dynamics that indicated an extensive capacity of microbes to catalyze bioremediation and potentially restore ecosystem health (Weiman *et al.*, 2021).

Oil eaters are present in low abundances when oil is absent. They are part of the so-called rare biosphere but are the first responders when oil appears, initiating oil-seekers movements, chemotaxis, and stimulation to express degradation genes. They then start to reproduce rapidly and soon dominate the contaminated ecosystems creating a microbial bloom in which they account for 90% of the community (Karthikeyan *et al.*, 2019). Following the exposure, microbes often exhibit cooperative metabolism among the community members, a system of metabolic pathways partitioning in which metabolites and intermediates are used by different species (Zengler & Zaramela, 2018). Another mechanism is by shuffling hydrocarbon degradation genes between and among community members via lateral gene transfers, spreading and widening the capacity of dealing with the oil in new hosts (Weiman *et al.*, 2021). This network or consortium of microbes that is formed can accomplish far more than a single species.

Besides new information that will guide mitigation and restoration strategies related to oil, the GoMRI provided an outline of core ecological and evolutionary principles regarding microbial responses and ecosystem function. They are in the foundation of how microbes from different ecosystems around the globe respond to diverse environmental disturbances (Weiman *et al.*, 2021). This knowledge is essential for the preparedness for stressors and catastrophes of any nature across broad scientific disciplines, far beyond the Gulf of Mexico.

2. *Defending corals from the inside-out*

Year after year corals face increasing challenges, from which we expect them to hopefully resist. Reduced water quality, overfishing, physical destruction, disease, and climate change-related effects, such as heatwaves, acidification, and increasing sea surface temperature, all of them can transform these diverse and productive ecosystems, which serves as shelters, food, and habitat for 25% of the known marine species (Bourne; Morrow & Webster, 2016). Corals are holobiont systems, i.e., they are formed by a eukaryotic host with all its associated microbial partners. This includes not only the photoautotrophic Symbiodiniaceae, but also viruses, bacteria, archaea, fungi, and protozoa (Deines; Lachnit & Bosch, 2017). One of those partners is notoriously known, the Symbiodiniaceae, which can provide > 90% of a coral's nutritional requirements (yet we know that corals obtain a fraction of their nutrients via heterotrophic metabolism). Other partners have only recently become know and have been reported as critical to the host's fitness and survival (Bourne; Morrow & Webster, 2016).

The coral host and its associated microorganisms live in an organized intimacy. Some partners are species-specific or even microhabitat-specific, which means that they can vary between different host species as well as colonize different microhabitat inside the host, such as coral mucus, skeleton, and gastric cavity (Vanwonterghem & Webster, 2020). The functions of the prokaryotic members of the holobiont can range from nutrient supply and recycling to protection against invading pathogens and against disturbances such as sea temperature increase (Bourne; Morrow & Webster, 2016). Thus, a holistic microbial ecosystem approach is needed to study microbially driven effects on holobiont health as well as their potential application in marine conservation and restoration practices. A possibility is to use putative beneficial microorganisms for preventing or healing coral unhealthy states after bleaching or diseases (Peixoto *et al.*, 2017; Rosado *et al.*, 2018).

3. The ancient art of cooking microbes

Now spotted on social media and bearer of Michelin stars (search for the Noma 2.0 restaurant in Copenhagen, a world-famous restaurant specialized in fermented food), fermentation is one of the most ancient processes of life. Early societies discovered the beneficial properties of microorganisms in the production and conservation of food thousands of years ago. The earliest archaeological evidence of human prepared fermentation dates from ~7,000 BC – an alcoholic drink made from fruit, rice, and honey. This ancient art of using microbes in the preparation of foods and beverages is part of the intangible heritage of every human community in the world (Anagnostopoulos & Tsaltas, 2019). Throughout the world, different types of traditional fermented foods and beverages are produced with peculiarities that vary from region to region. Most of them use acidic bacteria or yeasts and exert beneficial effects on gut microbiota, which is known nowadays to contribute to a multitude of aspects in the host biology, such as nutrition and metabolism, immune protection, brain development, and behavior (Amato *et al.*, 2021).

Due to their nutritional value and variety of sensory attributes, fermented foods have become part of the daily human intake in many countries. In general, the preparation process is sustainable and cheap, contributing to food security and sovereignty. Using fermentation to produce food has several advantages, such as (1) diminishing undesirable elements of the raw product; (2) improving food digestibility and nutrient availability; (3) enrichment of the food with vitamins and amino acids (prebiotics/probiotics effects); (4) reducing cooking time; (5) salvaging food waste; and (6) improving shelf-life and decreasing spoilage. Fermented products can impact many socio-economic aspects of people's lives as their production provides income and employment to millions of people around the world as well as can support rural development in both economic and social terms (Anagnostopoulos & Tsaltas, 2019).

Considering all those properties and the accessibility, the ancient art or science of using microbes for food production (zymology) should be reintroduced or reinforced and disseminated. A particularly interesting way of achieving so is through ethnozymology, i.e., the science of fermentation done by traditional human populations. It shows respect and interest to people's culture and heritage, this invisible biocultural landscape (Quave & Pieroni, 2014). Fermentation-based products are strongly connected with the territory of origin and people's traditions (Galimberti *et al.*, 2021), being popular throughout the world, from the *shoyu*, *natto*, *kimchi*, and *miso* in Asia to the table olives, cheese, curated meats, beer and wines in the Western countries. They have the potential to provide income and food security, diminishing inequalities and promoting healthier populations through gut microbiology, contributing to several SDG. Microbiology science can also help in this task by allowing a better understanding of the fermentation process, promoting biosafety, standardization, optimization, and better entrepreneurial opportunities.

4. Strong roots to reach for the sky

The future of agriculture is uncertain. This is a serious threat that climate change and climate-related disasters have imposed on humankind, which compromises global food security. Indeed, in some regions of the world, agriculture is already under siege, which is worsened by historical socio-economic problems. In general, agri-technological advances have been based on agrochemicals and crop breeding technologies, and the soil as a target for crop improvement has been largely overlooked (Rolfe; Griffiths & Ton, 2019). Nevertheless, by looking at the soil and its ability to sustain plants growth, we are indeed looking at the soil-associated and root-associated microbiomes, which are crucial for plant growth. For this reason, a new green revolution is needed to deal with climate change challenges and build a sustainable future in social, economic, and environmental terms. Microorganisms are the basis of this innovation.

The knowledge on Plant Growth-Promoting Microorganisms (PGPM) exists for at least 20 years, however, the massive use of PGPM in agrosystems is still limited. Nowadays, with the advances in meta-omics techniques, not only our knowledge on composition, function, and dynamics of cultivable and non-cultivable microorganisms has grown but also biotechnology provides a plethora of methods to enable the effective use of microorganisms in agrosystems (Rodriguez & Durán, 2020).

Restoration of degraded ecosystems can also benefit from the use of microorganisms, which is certainly encouraging. Land degradation and desertification have strong effects on global sustainability by affecting food production and water supply. By improving the restoration of degraded lands and combating desertification, we can promote soil fertility, climate regulation, and food and forage production, which is related to several SDG such as SDG 1 (no poverty), SDG 3 (good health and well-being), SDG 11 (sustainable cities and communities), SDG 13 (climate action), and SDG 15 (life on land) (Maestre; Solé & Singh, 2017).

By considering microorganisms for improving crop production and restoration, we aim to increase plant fitness, whether by promoting plant growth, protecting from pathogens, or conferring resistance to stresses. This phenomenon is known as "Cry for help", i.e., when a plant interacts with the surrounding microbial communities to alleviate different stresses. This occurs by the selection of specific strains from the natural microbiome that would increase plant advantage to a perturbation (Rodriguez & Durán, 2020). While we "cry for help" in soil degradation and loss of biodiversity and ecosystem services, the use of autochthonous microbes from the rhizosphere or biotechnology-engineered ones can certainly meet our needs. Nevertheless, this power must be acknowledged by stakeholders and decision-makers to encourage research and development in the field and enable this much-needed help to arrive in time.

5. Would you trust a muddy microbe?

Mangroves cover 75% of tropical and subtropical coastlines (Giri *et al.*, 2011), being distributed throughout 118 countries. Due to their high primary productivity (Bouillon *et al.*, 2008) and high carbon-storage capacity (Alongi, 2014), mangroves can play a crucial role as blue-carbon sinks (Mcleod *et al.*, 2011), provide valuable ecosystems services (Barbier *et al.*, 2011) and support adaptation to climate change (Lovelock & Duarte, 2019). However, when disturbed through land-use changes, mangroves can become a source of large quantities of greenhouse gases (GHG) (Kauffman *et al.*, 2020). Microbes are the main players that contribute to these and other mangrove ecosystem services (Allard *et al.*, 2020). They constitute the mangrove microbiome, which comprises taxonomically and functionally diverse microorganisms that participate in element cycling, organic matter decomposition and mineralization (Ochoa-Gómez *et al.*, 2019), and promote plant growth (Tong *et al.*, 2019), being directly or indirectly related to mangrove ecosystems services. For example, most of the carbon flux in tropical mangrove sediments is made by Bacteria and Fungi, which use carbon in the form of organic matter and contribute to the energy flow, nutrient recycling, and blue carbon sink (Thatoi *et al.*, 2013).

Historical data indicate that mangrove forests are considerably resilient, displaying a significant ability to adapt to changing conditions (Alongi, 2008). Mangroves from the northeast of Brazil, for instance, are subjected to high temperatures, low rainfall, and elevated evapotranspiration. Nevertheless, the microbiota associated with the root zones of such mangroves has been shown to be adapted to respond to these harsh conditions (Tavares *et al.*, 2021). The authors showed that those mangroves are pools of diverse and complex networks of prokaryotes. Those results are particularly interesting because, as adaptations to climate change, the mangroves in this region display a trend toward landward expansion, related to low rainfall and consequent saline intrusion (Godoy; Meirelles & Lacerda, 2018). The microbial communities in northeastern Brazil were shown to be adapted and possibly responsible for mediating the persistence and expansion of mangrove forests. Therefore, as in other ecosystems, microorganisms could be used for ecosystem recovery from anthropogenic disturbances or assisted ecological restoration based on the role of microbial diversity in maintaining the dynamic balance and functional equilibrium essential for mangrove sustainability.

6. Tiny argonauts

Microorganisms live in all environments on Earth – from any space occupied by macroorganisms to the deep subsurface and other extreme environments where they are the sole life forms. In the marine biome, which covers 70% of Earth's surface and includes coastal estuaries, mangroves, coral reefs, open ocean, and ocean deep, marine microbes thrive and can perform many pathways that are fundamental for life to exist on Earth. According to the Census of Marine Life, about 90% of the marine biomass is microbial, with a total number of cells in the order of 10^{29}, 100 times more diverse than plants and animals (Whitman; Coleman & Wiebe, 1998; Amaral-Zettler *et al.*, 2010).

One of the most basic roles is played by phototrophic microorganisms, which fix atmospheric global carbon – the biological carbon pump. They are responsible for fixing approximately half the global amounts of carbon per year while possessing only 1% of the trophic chain biomass. Another process, nitrogen fixation, is catalyzed by microbes and has fertilized seas and soils for billion years before man engineered the production of nitrogen fertilizers by the Haber-Bosch process. Beyond carbon and nitrogen fixation, marine microorganisms remineralize organic matter, which forms the basis of ocean food webs and global nutrient cycles. When this fixed carbon sinks, deposits, or is buried in the form of particulate organic matter to marine sediments, it provides the long-term sequestration of CO_2 from the atmosphere. This balance between released CO_2 by respiration and burial in the seabed is ultimately crucial for climate change (Cavicchioli *et al.*, 2019; García-Palacios *et al.*, 2021). Microbes also live as symbionts in most marine animals and provide antibiotics and pharmaceutics, such as anticancer drugs, crucial for maintaining our long lives.

Another opportunity those microorganisms provide is advanced fuel and electricity production. These advances are primordial for reaching the more ambitious goal of the 2015 Paris agreement, i.e., the world must not emit more than 580 gigatonnes of carbon dioxide before 2100 for a 50% chance of remaining below 1.5 °C of global warming. This means that most fossil fuels must remain unextracted (Welsby *et al.*, 2021). However, as worldwide energy use is projected to increase 50% by 2050 (EIA, 2019), cleaner and renewable energy sources stand out as eco-friendly solutions. Marine bioenergy stands out in this context by providing alternative sources, such as algae biomass to produce biofuels or microbial fuel cells devices for transforming chemical to electrical energy from a wide range of complex organic wastes (Keasling *et al.*, 2021). In general, wealthy countries dominate the biotechnology market due to the technology and financial investment required. Nevertheless, using low-cost technology, such as growing algae, as well as strengthening partnerships with wealthier countries provides an opportunity for developing countries to access this emerging market (Mazarrasa *et al.*, 2013).

Creating opportunities for the future

Those examples provide insights into how microbiology science provides solutions to produce more with less, reduce external inputs use, improve soil fertility and water bodies health, enhance food production, and help to prevent and treat infections. In addition, they strengthen ideas of bioeconomy business models based on microbes.

The differences those small beings can make in the future will require the cooperation, coordination, and collaboration of scientists from many fields from microbiology and other areas, such as engineering, social and economic sciences. Also, the initiatives should be properly funded and count on the collaboration of industries, governments, stakeholders, and local organized societies. The creation of a microbe-based bioeconomy is innovative and may sound strange to most people as there is a great lack of knowledge on the importance of microorganisms in society in general. Thus, it is also important to reinforce microbial literacy efforts, which can bring microorganisms and their profitable power closer to people's minds and lives.

CONCLUSIONS

Considering how human impacts put the future of the living world at serious risk, environmental microbiology and microbial ecology have provided knowledge that can provide microbial-based solutions. By showing how the 17 UN's Sustainable Development Goals can be approached by using microbes, I present alternatives for "business as usual" practices and raise awareness of the microbial world. Nevertheless, we cannot forget the urgent call for governments and institutions to shift policy away from economic growth and towards a conservation economy to refrain from environmental destruction to achieve a sustainable future.

The impact on or of this unseen microbial diversity should be addressed in ecosystem management as well as in the development of evidence-based microbial interventions and the exploration of biotechnological tools. The adaptive power provided by microorganisms may be the answer to adaptability in our changing world. Microorganisms may help us now or reign alone in the future.

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