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043
OCT 2024
ISSUES IN BRIEF

The Role of Microbiology in Sustainable Food Systems: Challenges and Opportunities

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During the 2021 United Nations General Assembly Science Summit, leaders discussed the role of biology in achieving the United Nations Sustainable Development Goals (SDGs). These goals, identified by the UN, create a plan for achieving a more sustainable future by 2030.[1] Here I will provide reasonable evidence to support the notion that these interdisciplinary global objectives are worth immediate and long-term pressures of political action, and also provide a blueprint for the role microbiology can play in achieving these goals.

There are various national strategies for addressing SDG integration. Due to the interdisciplinary nature of the SDGs, they are of crucial importance to be implemented into a national framework.[2] A balance between economic, social, and environmental developmental plans take part in the strategies to address the integrated nature of SDGs.

One SDG of particular interest is "Goal 2: No hunger", which sets the objective of ending hunger and achieving food security with improved nutrition through promoting sustainable agriculture by the year 2030.[3] The urgency of this goal can be indicated in 2020 estimates showing that about 1 in 10 people worldwide are suffering from hunger and that nearly 1 in 3 people lack regular access to adequate food.[4] Even in consideration of current global and political affairs with the Ukraine crisis, food shortages have been triggered among the world's poorest peoples. Together the Russian Federation and Ukraine supply global exports of approximately 30% of wheat, 20% of maize, and 80% of sunflower seed products.[3]

Additional SDGs are also involved in creating a sustainable future. The shared framework sets to make progress on objectives such as "Goal 13: Climate action" which calls for the urgency to combat and mitigate the climate crisis by limiting human-caused acceleration of global warming and greenhouse gas emissions. "Goal 12: Responsible consumption and production" vows to make fundamental changes to unsustainable ways our societies produce and consume goods. Furthermore, "Goal 11: Sustainable cities and communities" also occupies part of the blueprint for development in how humans live together on this planet. It includes advocacy for convenient access to public transportation and promoting sustainable land-use planning management. All together there are 17 total SDGs that participate in our path toward prosperity for people and the planet.

In a briefing held by the UN member states in March 2024, Ambassador of Chile to the United Nations, Paula Narváez, diagnoses our progress to be "not on track" to completing our SDGs by the 2030 deadline. She calls for scientific innovation to be leveraged as a powerful tool to ensure the development of a more sustainable future.

Microbes, being a fundamental form of life, are a great place to start asking biologically and socially fundamental questions. Microbes are among the earliest forms of life on Earth, preceding humans and plants. They can survive and thrive in extreme environments, from the deep sea, where high pressures and temperatures do not support the regular canopy of life, to the vacuum of space, where gravity or even matter does not have to be present for microbes to adapt and survive.[5,6,7] The adaptability and tolerance of this class of life is remarkable.

Microbes too play an integral role in the production of food. Microbes localized in the soil aid in the growth of plants and protect crops from diseases.[8] Additionally, microbes assist in food production often through processes like fermentation.[9] The U.S. Food and Drug Administration (FDA) has identified a list of Generally Recognized as Safe (GRAS) microorganisms that includes the microorganisms commonly implicated in the food supply chain, such as: *Acetobacter*, which is used to make vinegar; *Bacillus*, used to make soy sauce and natto; *Lactobacillus*, used to ferment lactose and make yogurt and cheeses; and *Saccharomyces*, yeasts that ferment sugars and are used to make wine, beer, and bread.[9,10]

Microbes make up the preferred source of enzymes across multiple industries due to their advantages in consistent and cost-effective production when compared to plant or animal sources.[8,11] A list of enzymes that are often used in food processing include:

α-Amylases: widely used in industries involving baking and brewing.

Glucoamylases: used in the baking and fermentation industries.

β-galactosidase: used in the dairy industry and as prebiotics for milk-based products.

Catalases: assists with the production of cheese and with food preservation.

Decarboxylases: important in fermentation processes.[8,9]

New companies such as AQUA Cultured Foods and Novonesis are utilizing microbes to create ingredients for dining foods. They enlist the use of fermentation, carried out by microbes to make specific ingredients that offer health benefits and even full foods such as 'seafood-less' seafood that utilizes these ingredients to make full meals which are 100% animal-free. As sustainable developmental goals are addressed, will the prominence of alternative food sources become a near future reality?

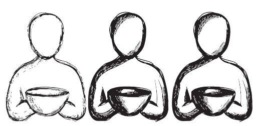
The Impact of Global Food Production on the Environment

Today, 30% of the world's total carbon emissions are represented by the global food production industry.[11] Additionally, half of the world's inhabitable land is used for agricultural purposes. The expansion of agriculture has been one of humanity's largest impacts on the environment. With significant increases in human population projected in the coming years, the growing demand for food production will only worsen.[11,12]

Mitigating some of these impacts has been a major challenge in environmental sciences. Great efforts have been made to reduce the impacts of agricultural development on the planet and its inhabitants. Of the agricultural land being used, 80% of it is dedicated to livestock while the other 20% is dedicated to crops.[11] As a civilization we know that we can reduce the need for agricultural lands through alternative technological advances, as well as implementing economic and social strategies to incentivize sustainable development.

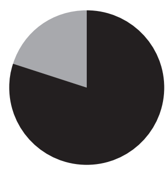
Livestock farming has many lasting environmental consequences. Substantial greenhouse gas emissions, grazing land use, acidification of terrestrial soils, and loss of biodiversity are just a few.[12] It also leads to the loss of ground freshwater, and eutrophication, which is the excess runoff of nutrients and chemicals into water bodies that often causes dense plant growth and death of animals due to lack of oxygen.[13] Cattle-based farming has more than doubled in the past sixty years, and that livestock farming is responsible for approximately one-third of global, human caused, greenhouse gas emissions.[14] This crisis shows an obvious, imminent need to readdress our current food systems.

Problem:



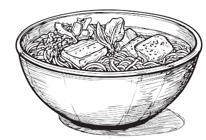
Nearly 1 in 3 people
lack access to adequate food

Land Use in Current Agricultural System:



Crop land use: 20%
Livestock land use: 80%

Main Outcome of Research:



Microbial-derived foods can
be environmentally conscious
and nutritionally valuable

Further increases in livestock production and land allocated to cattle-based farming are predicted in the coming decades.[14] This is often driven by population growth and the increase in average individual incomes making animal-based products more economically viable, specifically in middle-income countries.[15]

As we prepare for a more sustainable future in both developed and developing countries there needs to be a shift toward diets with fewer animal-farmed products. In particular, proteins can be sourced from plant-based and microbial-based alternatives. These diets can be nutritionally viable and set up large-scale food practices that are also more suitable for the long-term health of the planet. In order to address these problems, we need tools that will allow us to design technologies that influence large scale systems; many tools like this have already been developed.

Biology in Practical Applications

Biodesign is a term coined to describe the use of living organisms, such as microbes, in the design of products, technologies, solutions, and architecture to name just a few. Biodesign of the future is a wildly popular topic among bioengineers, designers, authors, science activists, and more. This topic is at the forefront of discussions among future-oriented material scientists who may be looking toward living organisms to provide new ways to develop bricks that are made of mycelium, which are more environmentally friendly than common materials such as concrete. Moreover, microorganisms have been used to initiate the establishment of living root bridges that use tree roots to grow a simple suspension bridge over a stream or river, like the ones present all over the Indian state of Meghalaya. Biodesign has revitalized discussions around the question: how can biology guide us in ways that advance our society? More specifically, what can biology help us do?

To consider this question let's look at some contemporary and practical examples of the use of microbial biology to sustain human development. Within the last decade, researchers in Japan have used a slime mold, a gelatinous fungus-like organism, to determine the most efficient way to organize the train transportation network in Tokyo.[16] The researchers shaped a petri dish, a growth container for cells used in laboratories, to the shape of Japan. In the location of major cities in the greater Tokyo area the researchers placed oat flakes, a slime mold's favorite food. And in place of Tokyo they placed the slime mold. The slime mold would then be allowed to grow and take direction toward their next meals. As the community spreads in search of its primary, and now abundant, food source it was creating routes to get to the food with the least amount of effort. With food acting as the major cities in the greater Tokyo metropolitan area, the slime mold was inadvertently delegated the task of designing the most efficient and robust network to connect the urban communities. As the slime mold grew for approximately 26 hours it stretched tendrils to reach and connect the food sources, as nodes in the system, to its initial inoculated spot — Tokyo. When repeated multiple times, the result created many versions of an adaptive network design that is biologically inspired by the slime mold's search for food. Its pattern corresponded with the position of cities surrounding the Tokyo metropolis with a minimal routed structure between the cities. Even when the pattern of growth looked differently, the researchers determined that the network was just as efficient as the previously established ones. This biologically inspired model lends awareness to how nature can provide answers to longstanding human transportation problems, with insight on how human-designed systems can be developed with high resistance to local failures.

Leaving transportation network design and going to a more consumable product industry, another example of the use of microbiology to supplement sustainable development can be seen in the textile dye industry. There, a company called Pili uses bacteria as little cell factories to create color. This approach is effective and renewable when compared to chemically sourcing dyes, which has harsher toxic reagents and creates larger pools of waste. Using bioengineered microbes that turn simple sugars into usable dyes for the textile industry will reduce large amounts waste and effectively address SDG "Goal 12: Responsible consumption and production." The dyes are specific and tunable to any color one might need and come out brilliant and in a wide variety of hues for fabrics. This solution to producing pigments can be scalable in size and can operate with large scale bioreactors too. Small bioreactors can be around 1 cubic meter, which is about the size of a washer and dryer unit. Larger bioreactors can hold upward of 10,000 liters and be 30 meters long or more, which is the size of about two city buses. This biotechnology will help the textile industry go green, a necessary remodel in our approach to SDGs as this industry is responsible for about 20% of global water pollution and 10% of global carbon emissions.[17] Both of those figures are growing as fast fashion for mass production of articles of clothing using low quality materials is rapidly growing in popularity among retailers. Biodesign is an old technique that partners human's design with nature's. Progress can be made to further marry them with newer technologies that support the synergy of the two.

Identification of Food System Alternatives

There are three such frameworks that are important alternatives to consider in the search for food systems with higher dependency: plant-based meat substitutes, cultured meats from animal cells grown in laboratories, and microbial derived proteins. Plant-based meat alternatives are dependent on substantial land use and also require large inputs of clean water, both of which might become more scarce with climate change.[18,19] Animal cell cultivation remains in very early stages of development with large unknowns regarding composition, nutritional value, and costs.[19] Microbial derived proteins are farther away from the effects of climate change as they are grown in bioreactors and decoupled from traditional agricultural methods.[19,20] The microbes undergo the fermentation process of turning sugars into alcohols, acids, and proteins.[21] The inputs to these bioreactors are minimal as, to start, they require only a few microbial cells and a broth consisting largely of sugars and amino acids which act as nutrients for the microbial cells.[21] Recent research even considers the use of seawater in industrial applications of biotechnology, which is more available than fresh water and agricultural land counterparts.[22] Biological fermentation has been applied at the industrial scale since the 1980s and allows for the conversion of biomass into various different substances.[21] With microbial derived proteins, the conversion of biomass into biologically relevant protein content that is digestible and has a high nutritional value is well established and widely accessible.[20,21]

> "An alternative that we need to investigate is the use of microorganisms in the production of sustainable foods, through converting biomass into something nutritionally valuable."

An alternative that we need to investigate is the use of microorganisms in the production of sustainable foods, through converting biomass into something nutritionally valuable. For many this represents an odd science fiction reality, but the idea may not be as far-fetched as it appears. Many commodities we value today are based in the process of microbial fermentation. Common food products made through fermentation include bread, beer, wine, vinegar, yogurt, cheese, chocolate, fermented fish, meat, and vegetables.[10,23] Similar efforts have been practiced around the globe in various ways. Take Indonesia for example, where for centuries people have been using the byproducts from tofu production and fermentation to develop a product called oncong, which is used as a meat substitute. In the United States, scientists from the University of North Carolina have used a yeast isolate from the gut microbiome of a wasp to produce what they call "bumblebeer," a fermented beer derivative that has a floral aftertaste.

Microorganisms such as yeasts, molds, and bacteria have been used for thousands of years to produce food products through fermentation processes.[21,24] Fermentation not only preserves food but can also improve its nutritional and sensory qualities.[24]

Why Should People Care?

Providing a growing population with healthy foods is an immediate challenge. Currently our food systems lack environmental sustainability while meeting the needs of a growing global population.[20] Many diet-related diseases are due to the low nutritional quality of foods contributing to the rise in incidence of diet-related obesity, coronary heart disease, stroke, and diabetes.[20] Unhealthy diets pose a greater risk of mortality than alcohol, drugs, and tobacco.[20] The demand for food is growing as population increases are globally affecting established systems. Coupled with the increase in population is the decrease in available land due to the rising need for development to maintain population expansions, degradation of land, and climate change. Additionally, climate disasters are set to rise in the future, making our response to changing conditions much more urgent.[12,17,20]

Plant-based food alternatives are comparatively less environmentally harmful than meat and livestock farming, which are dependent on stable climate conditions and consistent seasons, both of which are becoming more and more uncertain.[18,19] Additionally, they rely on intensive land cultivation, chemical pesticides, and fertilization, as well as heavy water use for irrigation, which is a challenge as, in many parts of the world, access to fresh water is becoming a scarcity.[13]

Broader Impacts

Policy makers need to set up protocols that will inform laboratories on safety and quality control to ensure that food production is sustainably sourced and done so in a manner that adjusts for our future needs. This will contribute to achieving the SDGs as we proceed toward a more sustainable society and will reduce the amount of land allocated for less sustainable practices such as livestock farming. In the United States, cattle production represents the largest share of total cash receipts for agricultural commodities. In 2022 its estimates peak at about $79 billion dollars of agricultural commodities.[25] This problem needs to be addressed systematically and must consider an interdisciplinary perspective, including public health, economics, and social affairs to ensure rollout is safely executed. By guaranteeing the implementation of food safety practices when producing microbially derived foods, we can ensure that food needs are met at a much larger scale while also safeguarding the public health of the general population.

Initiatives that are more beneficial for people in marginalized communities and businesses themselves should be considered to allow equity in an already established market. Many companies are turning to microbes for alternatively sourcing commodities such as textile dyes for fashion commerce, pharmaceutical components to be used in drug development, and even toiletries used in the beauty and personal care industries. Subsidies that economically assist companies that are implementing more sustainable sourcing of materials will promote new developments in our food systems that have positive environmental impacts.

The end goal of this document is to convince policy makers to incentivize sustainably sourced food ingredients, as well as expand understanding of what microorganisms can do for the food industry that lead to better, longer-term developmental outcomes. The outputs of this project are instrumental in informing FDA management of sustainably sourced alternatives at the federal, state, and local levels. Exploration of this topic will allow policy-relevant leaders to better serve the community with modern solutions to longstanding problems. Additionally, it will set up a systematic application for sustainably sourcing food through the use of microbially derived products and address the UN's SDG of ending hunger in an economically and agriculturally efficient manner.

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ISBN: 978-1-936727-18-6

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