

# What has biochemistry done for us? \_\_\_\_\_

## The algae revolution 2.0: the potential of algae for the production of food, feed, fuel and bioproducts – why we need it now

**Stephen Mayfield** and  
**Michael Burkart**  
(University of California,  
San Diego, USA)

Algae made our world possible, and it can help us make the future more sustainable; but we need to change the way we live and adopt new more efficient production systems, and we need to do that now. When the world was new, the atmosphere was mainly carbon dioxide, and no animal life was possible. Along came algae with the process of photosynthesis, and things began to change. Ancient cyanobacteria algae turned carbon dioxide into enormous sums of lipids, proteins and carbohydrates, while they secreted oxygen into the atmosphere. Over a billion years, as oxygen filled the air and algae filled the seas, animal life became possible. Eventually all that algae biomass became petroleum and natural gas, which for eons sat undisturbed in vast underground reservoirs, holding enormous sums of untapped energy. Less than 200 years ago humans learned to tap these energy reserves to create the world we know today, but in so doing, we have released millions of years of stored CO<sub>2</sub> back into the atmosphere. Algae can again help make the world a better place, but this will require new thinking and new ways of producing our food, feed and fuels. We need an algae revolution 2.0.

### The first algae revolution

Algae made our lives possible. You probably don't think about algae very often, and if you do, it's probably about the green slime growing in your local pond or the seaweed along the beach. Maybe you are a little more aware about the environment and know that algae are the primary producers in aquatic systems and are therefore the key organisms on which all aquatic life depends. But did you know that algae are the reason that any animal ever existed on this planet, including you, or that algae are the main reason we have planes, trains and automobiles, or that they are the primary drivers of our economy, and both the source of and a solution to climate change? Wait, what? Algae do all that? Yes, they do. Let us explain.

Four billion years ago, the atmosphere on earth was nothing like it is today. Carbon dioxide (CO<sub>2</sub>) made up to 70% of the atmosphere, and oxygen was in limited supply, with most of it trapped in CO<sub>2</sub>. There

were ancient prokaryotic chemotrophs, but no animals could survive in that environment, as there was no reduced carbon food source and no oxygen to allow for respiration. Then along came algae, cyanobacteria to be more precise, and things began to look up! It took some time for algae to work their magic on the new planet, but utilizing sunlight as an energy source, along with the newly developed process of photosynthesis, they began to turn CO<sub>2</sub> into algae biomass and secrete oxygen into the atmosphere. As the algae multiplied, the seas filled with fixed carbon in the form of their lipids, proteins and carbohydrates, and the atmosphere began to fill with oxygen. Over the next billion years or so, algae turned a once unforgiving planet into a world filled with organisms of every imaginable form. About 800 mn years ago, the first animals evolved, as there was now sufficient oxygen and food, in the form of reduced carbon, to make their lives possible. Later, about 400 mn years ago, vascular plants evolved from algae, allowing land-based herbivores to thrive, which eventually led to mammals appearing about 200 mn years ago, and finally

# What has biochemistry done for us?

to humans just a few million years ago. The lineage of life on earth as we know it today is very clear, and it all started with algae, and they remain an essential part of the environment today.

## Petroleum is fossil algae biomass

Given that algae fixed all of that CO<sub>2</sub> into algae biomass leads to one important question: Where did all that carbon go? This is also pretty clear; it went into enormous deposits that today we call fossil fuels, specifically, petroleum and natural gas. Most people likely know that coal is fossil plant matter, but not many know that petroleum and natural gas (methane) are primarily fossil algae accumulated over hundreds of millions or even billions of years. As algae 'fixed' CO<sub>2</sub> from the atmosphere into biomass, they settled to the bottom of shallow seas and were covered with silt and sand. After millions of years under high pressure and heat inside these geologic formations, this biomass transformed into crude oil, with the nitrogen, phosphate, metals and oxygen either precipitating or volatilizing, leaving primarily hydrocarbons behind. This petroleum sat underground in vast reserves for hundreds of millions of years, sequestering that carbon away from exposure to the atmosphere, but also holding enormous amounts of stored energy in these liquid and gaseous hydrocarbon deposits.

## Our current problem

It is not hard to identify the fundamental problem we have today. Almost 8 billion people inhabit the planet and consume more resources than the planet can sustainably produce. Burning fossil fuels to power the production, transportation and utilization of these resources offers the cheap and abundant power that makes modern life possible, and that allows most of us to enjoy a comparably high standard of living. If we look at the natural resources available, be that energy, food, water, minerals or other products, it is very clear that the rate of production cannot keep up with our current rate of consumption. Added to this dilemma is the fact that production and transportation of these goods requires great sums of energy, which we derive from the burning of fossil fuels, resulting in the release of billions of years of sequestered CO<sub>2</sub> back into the atmosphere within a very short time frame. It is not hard to see the consequences of our present life style: July 2021 was the hottest month humans have ever recorded on this planet, while 2020 was tied with 2016 as the hottest year ever recorded. As we write this, forest fires are burning out of control in many places around the world, while northern Europe and the USA have had record flooding this summer. If

that weren't enough, we also see the consequences of our modern lifestyles in the degradation of our oceans, forests and grasslands, with the corresponding loss of species, that some estimate as the greatest loss of species the earth has seen in millions of years. We are essentially destroying the ecosystems of our planet through over-consumption.

## The cause of the problem

Over the last 50 years the world's population has doubled, but during that same time consumption of energy, food and natural resources increased almost 80-fold. To say that is unsustainable doesn't begin to describe what this actually means to the future of our planet. We have to greatly reduce consumption, and quickly. If we don't do this in a designed and well-planned way, we will reduce consumption eventually, simply by running out of key resources or by their becoming so expensive that we can no longer afford to buy them. The question is: How do we do that in a way that doesn't plunge the world back into widespread poverty, like it was just 200 years ago, before we started exploiting fossil fuels? If we think of total world consumption (TC) as simply the number of people ( $P$ ) times the resources that each person consumes ( $R$ ), times what it costs (efficiency) to produce those resources ( $E$ ), we get the following equation:  $TC = P \times R \times E$ . If correct, there are three ways to drive down total world consumption: reduce the number of people, reduce the amount of resources each person consumes or reduce the cost (increase the efficiency) of producing those resources. Reducing the number of people is not a simple undertaking for any person or even a nation. Reducing world resource consumption is a bit out of our control, although we can all make choices as individuals that can greatly help! What we can do something about is focus on the efficiency of commodity production, especially food, fuel and bio-products. These production choices can have an enormous impact, if we choose to utilize those processes that require less energy, water and land to make products. This is where algae comes in.

## The algae revolution 2.0

### The base of the food web

After the first algae revolution, the one that made earth habitable for animals and deposited all the world's crude oil underground, algae kept on going. Today they make up the most diverse set of organisms on the planet and the foundation of the global food web. Take for instance omega-3 fatty acids. Medical science has known for decades that these polyunsaturated oils are essential for human health, including neural development and cardiovascular health, and their source

# What has biochemistry done for us? \_\_\_\_\_

had been commonly attributed to fish oils. However, fish do not make omega-3s; these essential oils are actually produced by marine algae and translated up the food chain to end up in the seafood that we eat. Based on this knowledge, algae aquaculture has been shown to provide the most sustainable means to produce omega-3s for medicines and nutritional supplements. This situation is emblematic of many opportunities for algae – sourcing our molecular and energy needs from organisms at the base of the ecosystem offers the most efficient and ecological option.

## **Food and feed**

Algae are the most productive photosynthetic organisms on the planet by far; some produce biomass at a rate 20 times faster than the most efficient terrestrial crops. This offers an opportunity for producing a variety of products, including food, feed, fuel and other commodities in a very efficient manner, and one that sequesters CO<sub>2</sub> during the production process. There are many ways to measure the efficiency of algae production, but one good example is protein production. Today the primary producer of protein on this planet is the soybean, which produces on average 350 pounds of protein per acre per year. In comparison, some algae can be 70% protein by weight and can easily produce 10,000 pounds of protein per acre per year and that protein can be highly nutritious, with an excellent amino acid composition. Even if we just replaced soybean with algae for protein production for animal feed, we could reduce TC significantly. If we used algae protein to engineer protein meals as direct replacement for animal meat, things like plant-based beef and chicken substitutes, we would also reduce energy, water and land use by almost 30-fold. That one change alone would allow the world to meet all of the UN's goals for carbon reduction for the next 20 years!

## **Bioplastics**

Given that plastics are derived from petroleum, and petroleum comes from ancient algae, can we make plastics from cultivated algae? Yes, we can! And the development of algae-sourced renewable plastics is already afoot. A major consideration in the development of this technology is what plastics should be replaced and what features should they embody. One highly desirable feature would be biodegradability, so that products do not end up as terrestrial or ocean garbage that pollutes our planet. This includes the avoidance of microplastics that have been found to concentrate in the food chain and eventually end up on our plates. It turns out that it is quite possible to make plastics from algae, and biodegradable polyurethanes have been made from algae that meet commercial quality specifications. We have found that these polyurethanes can degrade in the natural environment in less than a year. The challenge

will be scale and cost, but because polyurethanes are used in everything from high-end fashion shoes to commodity insulation, there is an opportunity to start with expensive, low-volume products, like shoes, and over time build to less valuable commodity products.

## **Biochemistry in new algae products**

As we move into advanced products developed from algae, there will be an increasing requirement for unique metabolites produced through metabolic engineering. Already some academic labs and companies are using synthetic biology to design and produce fatty acids and small molecules designed as polymer precursors. These pathways must be carefully planned, and the enzymes must be biochemically evaluated for substrate specificity and rate before expression in an algae host. Some programs require *in vitro* evolution of enzyme activity in order to achieve specific catalytic processes, and we expect that biochemistry will play a major role in the future development of algae-based products. These programs are highly interdisciplinary and involve not only biochemists, but chemists, engineers and polymer scientists to work together towards a common goal.

## **Economics of algae products**

The last decade saw a remarkable advance in algae cultivation and product development. This was fuelled in part by commercial investment into renewable fuels in the face of the mounting climate crisis. A consortium of academic and industrial researchers together demonstrated that renewable fuels from algae cultivation could indeed be produced for a reasonable cost (around \$8/gallon), such that economically competitive prices could be reached through economies of scale and governmental support. Unfortunately, this promising advancement was quashed by domestic and geopolitical forces, and large-scale adoption of algae-sourced renewable fuels remains unexplored. However, these efforts demonstrated the realistic ability to cultivate algae at scale for a variety of food, fuel and material needs, and provide proof of concept for large-scale replacement of petroleum products from algae biomass sometime in the future.

## **What challenges are there to overcome for algae to become widely used**

We are often asked: If algae are so great, why is there not widespread use of them today? That answer is complex, but really comes down to cost, and achieving the cost required to make algae a commodity requires economies of scale. All commodity products, be that food, feed or fuel, are products that have enormous scale, and with that comes economies of scale that make low cost possible. None of these products started out as commodities; they started as specialty products, and

## Algae Revolution 2.0



Algae as Food



Biodegradable Polymers

**Figure 1.** The Algae Revolution 2.0. The first algae revolution resulted in the formation of all of our fossil oil and natural gas reserves, while producing the oxygen that allowed animal life to flourish on this planet. The second algae revolution can help produce the food, feed, and renewable materials that the world will need if we are going to maintain a healthy planet and vibrant economy in the years to come.

over time gain the scale, and lowered costs, that allowed them to become commodities. Algae will follow the exact same path to widespread use, starting with specialty products like nutraceuticals and specialty chemicals, and then to animal feed and bulk protein, and finally to fuels. Over this developmental timeline, there will be many improvements to strains, production processes and even social acceptance, all parts of the development process that every commodity product goes through.

### Conclusion

Asking the world to change the way we grow, process and consume protein might take some time to implement, but the technology exists today – it is simply a matter of what we are willing to change in order to keep our ecosystems from collapsing. Sadly, it appears we are not yet prepared to change much about our daily lives; but as resources dwindle and prices rise, and as technology improves the taste and texture of engineered protein foods, preferences may change. Making the change to biodegradable, algae-sourced plastics may seem like a no-brainer in comparison. However, with plastic materials presently so inexpensive, so versatile and

so entrenched in our lives, it may take a significant commitment from consumers, and likely federal and state legislation, before any meaningful utilization of low carbon biodegradable plastics sees widespread adoption.

The world is at a tipping point. We have used fossil fuels to drive both industrial and agricultural revolutions and propelled the world populations, and consumption, to levels that are both unsustainable and potentially on a path to a catastrophic end. We must move to a more sustainable and efficient world. Algae can help us get there, but we need to act soon, with vision and resolve – we need an algae revolution 2.0 (Figure 1).

### Declaration of Conflicting Interests

SM and MB hold equity positions in Algenesis Inc., a company that could potentially benefit from this work.

### Funding

This work was supported by the US Department of Energy grant Productivity Enhanced Algae and Toolkits (DE-EE0008246). ■

# What has biochemistry done for us? \_\_\_\_\_

## Further Reading

- Phung Hai, T.A., Tessman, M., Neelakantan, N., et al. (2021) Renewable polyurethanes from sustainable biological precursors. *Biomacromolecules*. **22**, 1770–1794. DOI: 10.1021/acs.biomac.0c01610
- Gunawan, N.R., Tessman, M., Schreiman, A.C. et al. (2020) Rapid biodegradation of renewable polyurethane foams with identification of associated microorganisms and decomposition products. *Bioresour. Technol. Rep.* **11**, 100513. DOI: 10.1016/j.biteb.2020.100513
- Blatti, J.L., Michaud, J. and Burkart, M.D. (2013) Engineering fatty acid biosynthesis in microalgae for sustainable biodiesel. *Curr. Opin. Chem. Biol.* **17**, 496–505. DOI: 10.1016/j.cbpa.2013.04.007
- Shurin, J.B., Burkart, M.D., Mayfield, S.P. and Smith, V.H. (2016) Recent progress and future challenges in algal biofuel production. *F1000Res*. **5**. DOI: 10.12688/f1000research.9217.1
- Torres-Tiji, Y., Fields, F.J., and Mayfield, S.P. (2020) Microalgae as a future food source. *Biotechnol. Adv.* **41**, 107536. DOI: 10.1016/j.biotechadv.2020.107536



*Stephen Mayfield is a distinguished professor of biology at UC San Diego. Steve received BS degrees in biochemistry and plant biology from Cal Poly State University in San Luis Obispo and a PhD in molecular genetics from UC Berkeley. Following a post-doctoral fellowship at the University of Geneva Switzerland he returned to California as an assistant professor at the Scripps Research Institute where he remained for 22 years becoming the Dean of Biology, before joining UC San Diego in 2009. In addition to running his research group and university research centre, Steve is a scientific founder and CEO of Algenesis Materials, a company dedicated to making sustainable and biodegradable polyurethane products. Prior to Algenesis, Steve also founded Rincon Pharmaceutical in 2005, Sapphire Energy in 2007 and Triton Health and Nutrition in 2013. Email: [smayfield@ucsd.edu](mailto:smayfield@ucsd.edu)*



*Mike Burkart grew up in Texas and received a BA in chemistry from Rice University in 1994 and a PhD from the Scripps Research Institute in 1999. After an NIH post-doctoral fellowship at Harvard Medical School, he initiated his own research group at the University of California, San Diego, in 2002. He is currently a professor of chemistry and biochemistry at UC San Diego and director of the Center for Renewable Materials. His research includes natural product synthesis, biosynthesis and metabolic engineering, and through collaborative efforts in renewable and biodegradable materials with Steve Mayfield, he has developed algae-derived surfboards, flip-flops and shoes.*