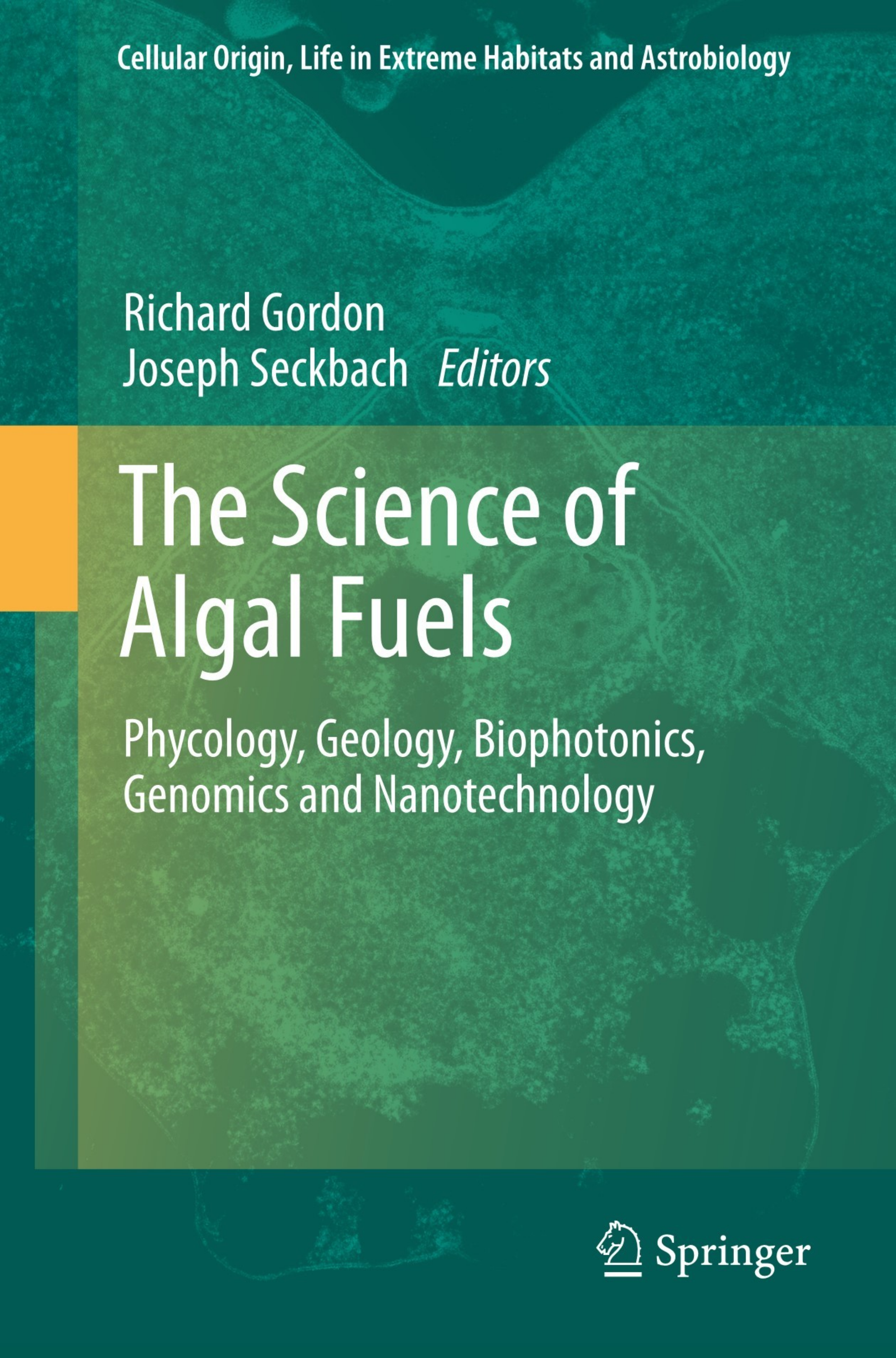

Cellular Origin, Life in Extreme Habitats and Astrobiology

Richard Gordon
Joseph Seckbach *Editors*

The Science of Algal Fuels

Phycology, Geology, Biophotonics, Genomics and Nanotechnology

Springer

THE SCIENCE OF ALGAL FUELS

Cellular Origin, Life in Extreme Habitats and Astrobiology

Volume 25

Series Editor:

Joseph Seckbach
The Hebrew University of Jerusalem, Jerusalem, Israel

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DEDICATION

Finished and dedicated to Leland Terrell Gordon on his 38th birthday, and to his nephew Raleigh Gordon on his first birthday.
… in Wildness is the preservation of the World.

–Henry David Thoreau, *Walking* (1862)

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BRIEF INTRODUCTION TO *THE SCIENCE OF ALGAL FUELS: PHYCOLOGY, GEOLOGY, BIOPHOTONICS, GENOMICS, AND NANOTECHNOLOGY*

The increasing global demand on fossil petroleum reserves and political manipulation of crude oil have encouraged scientists and politicians to look for alternative sources of energy.

This volume, *The Science of Algal Fuels* (volume 25 of *COLE*), contains 25 chapters dealing with biofuels contributed by experts from numerous countries. It covers several aspects of algal products, one being "oilgae from algae," mainly oils and fuels for engines. Among the prominent algal groups that participate in this process are the diatoms and green algae (*Chlorophyceae*). Their metabolism and breeding play an important role in biomass and extraction of crude oil and algal fuel. There is a strong relation between solar energy influencing algal culture and the photobiology of lipid metabolism.

Currently, many international meetings and conferences on biofuel are taking place in many countries, and several new books and proceedings of conferences have appeared on this topic. All this indicates that this field is "hot" and in the forefront of applied bioscience.

The advantage of extracting natural products from microalgae and seaweeds is that it is easy to culture them on a large scale. They have fast natural growth and yield abundant biomass within a short period. There is also the possibility to grow seaweeds in an "agricultural growing system."

Nanotechnology, one of the techniques for producing biofuels, is described in this volume. Extraction from micro- and macroalgae to produce biofuel is made after harvesting them from their habitats, namely, freshwater, seawater, and wastewater. Such production of biofuel from microalgae and seaweeds via biorefineries occurs in several countries. We believe that there is a great future for extracting high yields of biomass from microalgae and seaweeds for the production of biodiesel, fuel, and oils.

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FOREWORD

The Production of Algal Biofuels

Biofuels from algae are drawing much research, as reflected in this volume. But what about the perspectives for the (commercial) production of such biofuels?

EASY ALGAL OIL?

In recent decades, the world economy has been heavily dependent on “easy oil,” mineral oil which is produced easily at low cost and in large amounts (e.g., Dale et al., 2011). As the age of “easy oil” is drawing to a close (e.g., Dale et al., 2011), one of the matters arising is whether there is “easy algal oil” to replace “easy mineral oil.”

Commercial cultivation of autotrophic oil producing microalgae (“oilalgae”) dates back to the 1950s (Goldman, 1979; Vonshak and Richmond, 1988). The commercial cultivation of autotrophic microalgae has since then served food and feed production, by supplying oil (lipids), algae, carotene, and astaxanthin (Apt and Behrens, 1999; Trautwein, 2001; Spolaore et al., 2006; Sahena et al., 2009; Gachon et al., 2010; Rubio-Rodriguez et al., 2010; Larkum et al., 2012). Commercial cultivation of macroalgae was also significant in the 1950s (Cheng, 1969) and has expanded much since then, serving among others the food, feed, and pharmaceutical industries and the supply of agar and carrageenan (Huguenin, 1976; Bird and Benson, 1987; Renn, 1997; Ask and Azanza, 2002; Lüning and Pang, 2003; Peng et al., 2009; Bezerra and Marinho-Soriano, 2010; Kraan, 2012).

The “oil crisis” of the early 1970s triggered proposals to cultivate autotrophic microalgae as source of oil for energy generation, which in turn did lead to a substantial research effort regarding “oilalgae” (Goldman, 1979). In the same decade, the potential contribution of photosynthetically generated microalgal H_2 to energy supply drew increased attention (Melis, 2002), whereas the production of macroalgal biomass for biofuel (ethanol, methane) production was also researched (Bird and Benson, 1987). Since then, substantial research on algal biofuels has continued (Melis, 2002; Mata et al., 2010; Bernard, 2011; Hallenbeck et al., 2012; Kraan, 2012). Recent years have been characterized by a marked increase in research investigating the energetic potential of algae. This research has regarded both microalgae and macroalgae and has also included isoprenoids and butanol, with research regarding biofuels based on microalgal oil dominating the field (Bernard, 2011; Jones and Mayfield, 2011; Konur, 2011; Kraan, 2012; Lohr et al., 2012; Potts et al., 2012; Wargacki et al., 2012).

Research has so far not led to commercial microalgal oil-based biofuel production nor to the commercial production of other algal biofuels (van Beilen, 2010; Sun et al., 2011). Given present technologies, microalgal oil is characterized by high cost (van Beilen, 2011; Petkov et al., 2012). Algal lipid-based biofuels produced with present technologies appear to be more expensive than similar current terrestrial biofuels, with biofuels from microalgae cultivated in bioreactors being more expensive than biofuels from microalgae grown in open systems such as ponds (Agusdinata et al., 2011; Amer et al., 2011; van Beilen, 2011; Ghasemi et al., 2012; Petkov et al., 2012).

From available research on technologies which put the production of microalgal oil-based biofuels center stage, it would seem that, differently from mineral oil, there is apparently as yet no "easy microalgal oil," which is easily produced on a large scale at low cost.

ENERGETIC RETURN ON (ENERGY) INVESTMENT

A substantial problem for the large-scale production of microalgal oil-based biofuels regards the EROI, the energetic return on (energy) investment over the biofuel life cycle. It has been argued that the EROI for a major energy source should be >5, as this would allow for maintaining quality of life in the absence of readily available abundant fossil energy (Hall et al., 2009). The criterion that the EROI should be >5 is met by several emerging energy technologies such as wind power and photovoltaic power (Kubiszewski et al., 2010; Raugei et al., 2012). However, available life cycle assessments suggest that with present technologies the EROI for algal biofuels is <1 or somewhat larger than 1 (Reijnders, 2012). Increasing oil and algal biomass yields, lowering energy inputs, and aiming at multifunctional algae have emerged in proposals to improve the EROI of microalgal oil-based biofuels (Clarens et al., 2011; Reijnders, 2012). As to the latter: microalgae can be, e.g., used to treat wastes or emissions and as feedstock for biorefineries generating valuable coproducts besides algal oil (e.g., Oswald et al., 1957; Christenson and Sims, 2011; Rosenberg et al., 2011; Ahmed et al., 2012). However, available life cycle assessments studying combinations of such improvements in biofuel life cycles which have an upward effect on the EROI still do not show EROIs >5 (Chowdhry et al., 2012; Reijnders, 2012; Vasudevan et al., 2012). The few available studies which have looked at the life cycles of other algal biofuels such as ethanol from cyanobacteria ("blue-green algae") (Luo et al., 2010), methanol from microalgae (Liu and Ma, 2009), and methane from offshore-cultivated seaweed (Langlois et al., 2012) also suggest EROIs <5.

Moreover, concerns have been raised about the actual achievability of several of the major improvements featuring in life cycle assessments of future technologies for the production of microalgal oil-based biofuels (e.g., van Beilen, 2011).

A case in point is the achievability of major increases in oil and biomass yields from open systems which seem more suitable than photobioreactors for achieving large-scale algal oil production at relatively low cost (Hall and Benemann, 2011; Sun et al., 2011). Yields from open systems in the order of 70–90 Mg dry weight ha^{-1} $year^{-1}$ and 25–40+% oil appear to be important for achieving relatively high EROIs (though not >5) for algal lipid-based biofuels (Reijnders, 2012). One of the reasons for concern about the achievability of such yields is linked to the common difference in "greenness" between surface waters and terrestrial ecosystems with sufficient moisture. The latter tend to be much greener than the former. A main reason for this difference in "greenness" is that phytoplankton (to which "oilalgae" belong) contributes almost half to worldwide photosynthesis but accounts for less than 1% of the photosynthetic biomass present worldwide (Falkowski, 2012). The low share of microalgae in worldwide photosynthetic biomass is linked to grazing by zooplankton and insect larvae and the activity of algal pathogens such as viruses and parasites (Day et al., 2012). Also, infections by competing microorganisms are a major problem in open systems for the cultivation of microalgae. The way to circumvent much of these problems and to produce intended microalgae in commercial open systems is so far to use extreme conditions such as very high pH or salt concentrations (Reijnders, 2012). Such extreme conditions are not conducive to high biomass yields and also necessitate substantial energy inputs in the algal biofuel life cycle for maintaining extreme conditions and for wastewater treatment (Reijnders, 2012).

It has been suggested to increase the microalgal biomass yield by genetically engineered truncated antennae (Ort et al., 2011). However, algae with truncated antennae appear to be less competitive than their counterparts with full antennae, and this may have a negative impact on the yield of intended microalgal biomass in open systems where contamination by full-antenna algae may occur (Ort et al., 2011). And the assumption that high biomass and oil yields can be combined seems to take insufficiently into account that photon demand increases at high lipid contents (Wilhelm and Jacob, 2012). Another problem is the difference between well-controlled field experiments with open ponds, which have been used to support estimates of high future yields, and actual commercial practice. Vonshak and Richmond (1988) found the commercial production of *Spirulina* to be a factor 5–6 lower than in well-controlled field experiments. Whether large-scale production of microalgal oil with an EROI > 5 will emerge from future research and development focusing on algal biofuel production is as yet highly uncertain.

ALGAL BIOFUELS AS COPRODUCT

On the other hand, there is, as pointed out above, the certainty of a current commercial market for macro- and microalgae and constituents thereof. This market may well grow substantially in the future. Algae may in the future be used as a platform for a wider range of substances (e.g., Renn, 1997; Kraan, 2012). And the presence of the long-chain *n*-3 polyunsaturated fatty acids in microalgal oil is a major asset regarding future food consumption. Long-chain *n*-3 polyunsaturated fatty acids, such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), are valued as constituents of healthy diets (Graham et al., 2004; Bockisch, 2010; Gogus and Smith, 2010). Ironically these long-chain *n*-3 polyunsaturated fatty acids are problematic in terms of fuel properties because they have relatively poor oxidative stability and ignition quality (Bucy et al., 2012).

The presence of eicosapentaenoic acid and docosahexaenoic acid in the human body is currently to a large extent based on the consumption of fish which in turn ultimately acquire these fatty acids fully or mainly from the consumption of algae (Graham et al., 2004; Sanders, 2009; Bockisch, 2010; Gogus and Smith, 2010). However, in view of the (potential) overexploitation of fish stocks, the supply of fish-based long-chain *n*-3 polyunsaturated fatty acids is limited (Graham et al., 2004; Bockisch, 2010). Also, intervention studies have shown health benefits of algal long-chain *n*-3 polyunsaturated fatty acids (Holub, 2009). Furthermore, one might argue that the direct consumption of microalgal long-chain *n*-3 polyunsaturated fatty acids by humans might be less of an environmental burden and that the problem of co-consumption of toxicants such as methylmercury and PCBs might be reduced if compared with consuming fish (e.g., Oken et al., 2012). Thus, there might well be scope for an expanded production of "oilalgae" for food in the future.

The future production of algae and constituents thereof is likely to be linked with the coproduction of substantial amounts or organic material which might be converted into biofuels. The cultivation of microalgae may be associated with a substantial production of organic compounds leaking into their aquatic environment (Day et al., 2012). And processing of macro- and microalgae might generate substantial amounts of organic compounds that cannot be marketed as food, feed, or ingredients for products. Such organic coproducts from the cultivation and processing of algae might be used for the production of biofuels (e.g., Langlois et al., 2012). As the handling of such coproducts might be argued to rather be in the category of waste treatment, one might moreover argue that the criterion of an EROI > 5 should not necessarily apply. Thus, converting organic coproducts of cultivating and processing algae into biofuels might well make a limited but valuable contribution to future energy supply.

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PREFACE

Success of a book like this depends on many people, the authors, the reviewers, and the publishing staff. Algal fuels made the news during the 2012 US presidential campaign, with remarks by Republican contender Newt Gingrich:

> The President [Barack Obama] says, “the Republicans have three strategies: drilling, drilling drilling.” And I want to say tonight, Mr. President this is one of the rare occasions where I can say you are right…. The President said we have to be practical. Drilling won’t solve it. And then he offered his practical solution. Anybody here remember what it was? Algae. Algae. I mean I think this summer as gas prices keep going up, one of our campaign techniques should be to go to gas stations with jars of algae and say to people would you rather have the Gingrich solution of drilling and having more oil or would you like to try to put this in your gas tank…. [A]fter he explained drilling doesn’t work, the President explains we’ve had this great breakthrough of natural gas. That we now have thanks to new technology over 100 year supply of natural gas. That in fact we’re going to create 600 k new jobs in next decade out of natural gas…. [H]ow does the President think we discovered the natural gas? (Fox News, 2012)

In response to this, RG wrote to Michael Krull, Campaign Manager, Newt 2012:

> Newt’s quip of filling up our gas tanks with algae is indeed amusing. However, the USA dropped the ball in 1995 by terminating a 15 year project to develop algal fuels, at a time oil prices dropped, and is now playing catch-up. It’s a long range strategy that may deserve some R&D, so a more subtle message that does not alienate the algal fuel community might be worth developing.

Afterward Gingrich added: “By the way I’m pro research into algae” (Calhoun, 2012). But algae entrepreneurs nevertheless got upset (AlgaeIndustry Magazine.com, 2012):

> Before long, Mr. Gingrich will be pumping our product into his car’s gas tank; I certainly look forward to seeing that photograph…. This technology enables the production of ethanol for less than \$1.00 per gallon using algae, sunlight, carbon dioxide and saltwater. Our novel techniques are projected to produce 6,000 gallons of ethanol per acre per year (compared to corn at 400 gallons/acre/year and sugar cane at 800 gallons/acre/year), plus we have the very important added benefit of consuming carbon dioxide from industrial sources. (Woods, 2012)

Well, maybe. We would all like to project that algae will produce cheap, plentiful biofuels, biodiesel, or ethanol, but despite hundreds of contestants in this race, “we ain’t there yet,” in terms of having eliminated the need to pump oil out of the ground. In particular, the use of CO_2 from industrial sources (cf. Ladd and Venter, 2008) may prove counterproductive, because CO_2-producing industries may not be considered sustainable and because their total output, when converted to biofuels, may be inadequate for our needs: industrial processes in the USA emit 300×10^6 metric tons CO_2 equivalent per year, which is 5% of that attributed to energy at 6000×10^6 metric tons CO_2 equivalent per year (Table ES-4 in Hockstad and Cook, 2012). So while we all have a long way to go, we hope that the chapters in this book will be stepping stones to sustainable biofuels for everyone.

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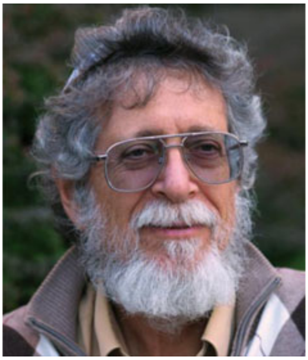

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