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The Nonsense of Biofuels

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Fossil fuels, like mineral oil, coal, and natural gas, are derived from the biomass of ancient times. As such, they are indirect products of photosynthesis. It is therefore appropriate to ask whether we can use currently available biomass and convert it into biofuels like biodiesel and biogas. Biohydrogen might be another option. Often one can read that biofuels are CO_2-neutral and therefore a weapon against global warming. Their production is also supposed to reduce the amount of petrol and natural gas to be imported into many countries, thus making them less dependent on energy import. In the following, I shall discuss the efficiencies of the processes required to produce biofuels, compare them with alternatives, draw the obvious conclusions, and present some visions.

The Efficiency of Photosynthesis

First it is necessary to discuss the efficiency of photosynthesis and to present some ideas on how to improve photosynthesis and therefore enhance biomass production. Photosynthesis comprises so-called light reactions and dark reactions. In the light reactions, the light is absorbed by the photosynthetic pigments and the energy is transferred to the reaction centers where the primary charge separation and a transmembrane transport of electrons takes place. Subsequent electron- and proton-transfer reactions lead to the synthesis of the universal biological energy carrier ATP from ADP and inorganic phosphate, and $NADP^+$ is reduced to NADPH. In the following dark reactions, NADPH and ATP are used to take carbon dioxide from the atmosphere and use it for the synthesis of carbohydrates.

The production of biofuels constitutes an extremely inefficient land use

The photosynthetic pigments of plants can only absorb and use 47% (related to energy) of the light of the sun ("photosynthetic active radiation"). Green light, UV, and IR irradiation are not used. In theory, 8 photons are required to reduce 2 molecules of $NADP^+$ to NADPH, in reality, 9.4 photons are found to be necessary for this purpose. Knowing the average energy of the photons and the energy stored in the form of NADPH, it is easy to calculate that only 11.8% of the energy of sunlight is stored in the form of NADPH. This value then also will be close to the upper limit for the efficiency of the photosynthetic production of biohydrogen.

Photosynthesis is most efficient at low light intensities. It is already saturated at 20% of full sunlight and 80% of the light is not used. The limitations are most likely caused by the electron flow through the photosynthetic reaction centers. In addition, high light intensities lead to photodamage of a central protein subunit of the photosynthetic apparatus: plants repair their photosystem II reaction center by exchanging the D1 protein three times per hour. 3.5 billion years of evolution have not been long enough to develop a mechanism for preventing the photodamage.

The dark reactions are limited by an insufficient discrimination between CO_2 and O_2 by the enzyme RuBisCO, which inserts CO_2 into ribulose-1,5-bisphosphate. One third of the energy of the absorbed photons is believed to be required to remove the product of the O_2 insertion, 2-phosphoglycolate. The second limitation is caused by the fact that photosynthesis depends on the availability of sufficient amounts of water, a condition that is not met during much of the day.

As a result of the limitations described above, 4.5% is considered as the upper limit of the photosynthetic efficiency of C_3 plants. However, in reality, values of only around 1% are observed, even for rapidly growing trees like poplars.

Biofuels

When the yields of biofuels per hectare are known, one can easily calculate how much of the energy of the sunlight is stored in the biofuels. For German "biodiesel" which is based on rapeseed, it is less than 0.1%, for bioethanol less than 0.2%, and for biogas around 0.3%. However, these values even do not take into account that more than 50% of the energy stored in the biofuel had to be invested in order to obtain the biomass (for producing fertilizers and pesticides, for ploughing the fields, for transport) and the chemical conversion into the respective biofuel. This energy normally is derived from fossil fuels. The produc-

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tion and use of biofuels therefore is not CO_2-neutral. In particular, the energy input is very large for the production of bioethanol from wheat or maize, and some scientists doubt that there is a net gain of energy. Certainly the reduction of CO_2 release is marginal. The yield of second-generation biofuels where entire plants are used may be doubled. However, the energy input probably also increases. For example, in the production of biodiesel by the Fischer–Tropsch process, hydrogen has to be added because syngas obtained from biomass contains insufficient amounts of hydrogen. Taken together, the production of biofuels constitutes an extremely inefficient land use. This statement is true also for the production of bioethanol from sugar cane in Brazil.

The Alternative

Commercially available photovoltaic cells already possess a conversion efficiency for sunlight of more than 15%, the electric energy produced can be stored in electric batteries without major losses. This is about 150 times better than the storage of the energy from sunlight in biofuels. In addition, 80% of the energy stored in the battery is used for the propulsion of a car by an electric engine, whereas a combustion engine uses only around 20% of the energy of the gasoline for driving the wheels. Both facts together lead to the conclusion that the combination photovoltaic cells/electric battery/electric engine uses the available land 600 times better than the combination biomass/biofuels/combustion engine.

Improving Photosynthesis

It is obvious that there is some room to improve the primary steps of photosynthesis and of biomass production. First, it might be possible to increase the spectral range of the absorbable light by modifying the pigments of the light-harvesting complexes. Having pigments absorbing UV light and green light could contribute, although the prospect of having black leaves is not attractive. More realistically, one should try to change the relation of light-harvesting pigments to reaction centers by reducing the number of light-harvesting complexes funneling energy to one reaction center. This manipulation would reduce the electron flow through the reaction centers and reduce photodamage and the saturation at high light intensities. Engineering RuBisCO to increase its ability to discriminate between CO_2 and O_2 is still a valuable aim, in particular in the light of the discovery that the RuBisCO of red algae is much better than the plant RuBisCO in this respect.

We should not grow plants for biofuel production

Biohydrogen production, currently employing hydrogenases connected to the reducing side of photosystem I, will only be able to compete with photovoltaic cells followed by water electrolysis if the water-splitting photosystem II can be engineered to produce hydrogen directly, either by itself or through an intermediate electron acceptor with a suited redox potential. Hydrogen production by photosystem II would reduce the number of photons required by more than 50%. However, this protein engineering task appears to be insurmountable at present.

Microalgae have been advertised as the ideal candidates for biofuel production. There are many unsupported claims about their efficiency, some even exceeding the theoretical limits of photosynthetic efficiency. I concede that microalgae could be better than land plants because of the absence of nonphotosynthetic cells and the continuous availability of water. However, the existence of photoinhibition and a poor RuBisCO will limit the advantages of microalgae together with the demands for growing and harvesting them.

Visions

Improving photosynthesis, although a highly important goal towards securing food security, cannot change the superiority of the combination photovoltaic cells/electric battery/electric engine. The major limitation of the latter system lies in the low storage capacity of current electric batteries. With gratification I read in this journal an article on a polymer tin sulfur lithium ion battery with a an energy storage capacity 10 times that of available lithium ion batteries.[1] If these batteries can be developed to marketability, cars can be built that have the same cruising range as the presently available fuel/combustion-engine-based vehicles. At the same time, such batteries will help to store electric energy. In a visionary view, storage of electric energy would not be required if superconducting electricity cables would be available. In this case, a limited number of photovoltaic fields located in various time zones around the globe, say, one in North Africa or the Kalahari, one in Eastern Asia/Australia, and one in Mexico, connected by such cables and to the consumer would continuously supply electric energy.

Recommendations

Because of the low photosynthetic efficiency and the competition of energy plants with food plants for agricultural land, we should not grow plants for biofuel production. The growth of such energy plants will undoubtedly lead to an increase in food prices, which will predominantly hit poorer people. The best use of the biomass lies in its conversion into valuable building blocks for chemical syntheses. Usage of the available biomass for heating purposes or for generating electricity in power stations, thus replacing fossil fuels, is preferable over biofuel production. The saved fuels can be used for transportation purposes. Clearing rainforests in the tropics and converting them into oil palm plantations is highly dangerous because the underlying layers of peat are oxidized and much more CO_2 is released by the oxidation of organic soil material than can be fixed by the oil palms. The rainforests possess an important role for the climate and constitute a valuable resource for novel compounds for drug discovery. With respect to the carbon footprint, it would be even much better to reforest the land used to grow energy plants, because at a 1%

photosynthetic efficiency, growing trees would fix around 2.7 kg of CO_2 per square meter, whereas biofuels produced with a net efficiency of 0.1 % would only replace fossil fuels which would release about 0.31 kg CO_2 per m^2 upon combustion!

The future of our individual transport has to be electric!

[1] J. Hassoun, B. Scrosati, *Angew. Chem.* **2010**, *122*, 2421–2424; *Angew. Chem. Int. Ed.* **2010**, *49*, 2371–2374.

