Polymers for Sustainability

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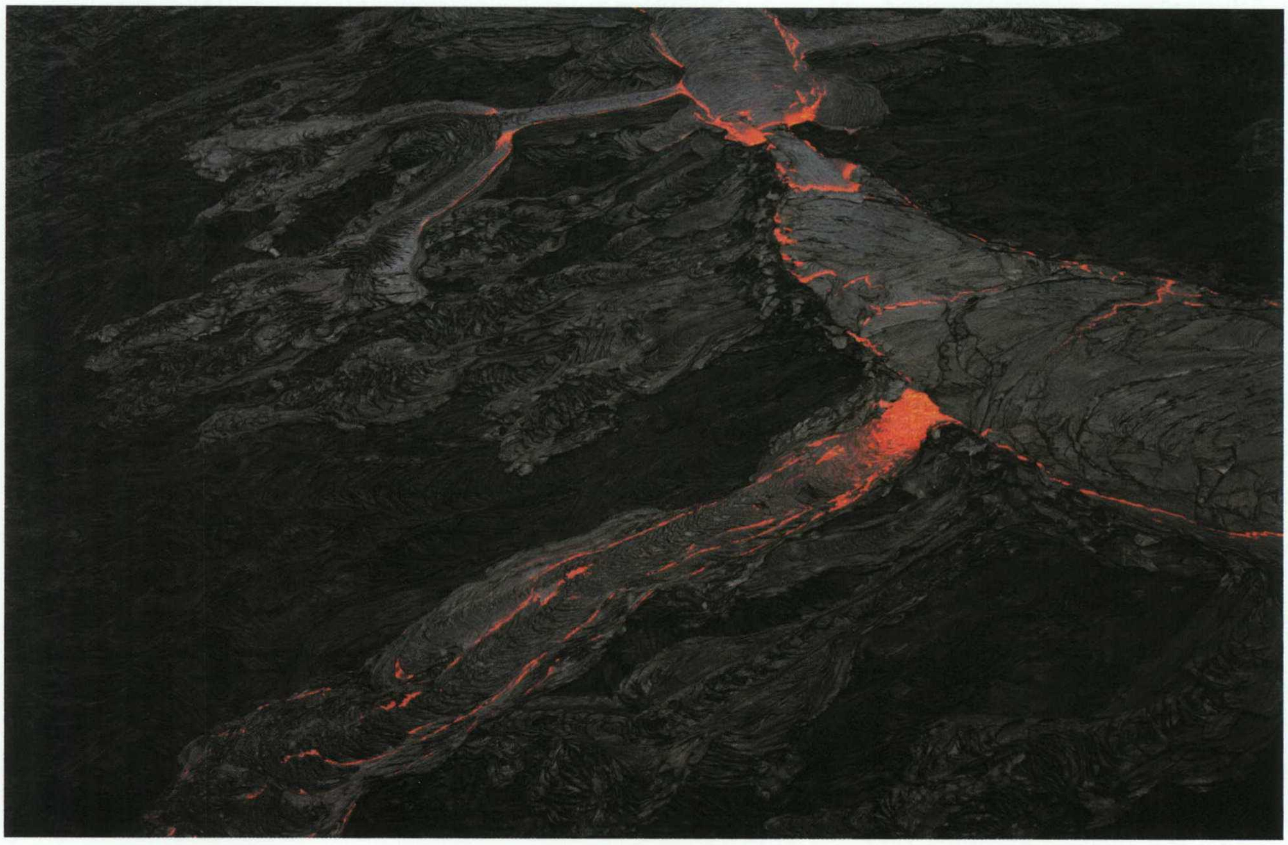
Mankind must begin making efforts to curb the pace of coal and petroleum consumption, while at the same time accelerating processes that bring the circulation of carbon compounds "full circle"

As far as the circulation of matter is concerned, the Earth can be considered to have been a closed system with a stable mass for at least the last billion years. Under steady states, when the proportions between individual chemical compounds remain relatively stable, chemical elements are exchanged through simple reversible transformations or via cyclical processes. The appearance of new factors altering the course of these processes can trigger a shift in this steady state. One of the most important such cycles on Earth is the carbon cycle.

Carbon in demand

Carbon represents around 0.018% of the mass of the Earth's crust. Before life arose on our planet, carbon occurred bound in minerals (mainly as carbonates) and in the form of carbon dioxide and monoxide. Back then, the basic forces driving the terrestrial carbon cycle were volcanic processes releasing carbon dioxide and chemical reactions with base compounds binding carbon dioxide in insoluble or sparingly soluble inorganic compounds. The concentration of CO_2 in the Earth's atmosphere was then significantly higher than it is now. The system of carbon circulation was stable and probably slow-paced.



Mila Zinkova

Before living organisms became involved in the global carbon cycle, the most significant factor was carbon dioxide released by volcanic activity, such as that now observed in Hawaii and elsewhere

To give some comparison, we can note that the quantity of carbon dioxide currently emitted into the atmosphere by volcanic processes amounts to about 200 million tons per year. Even if carbon dioxide emissions were 10 times greater in the period prior to the emergence of life on Earth, that would still represent just 1% of the CO_2 that currently gets emitted annually as a consequence of the breakdown of organic matter.

Mankind changes the world

A distinct upswing in the cycle of transformations involving carbon-containing compounds occurred when the first organisms capable of photosynthesis appeared around 3-4 billion years ago. The rise of life on Earth led to a shift in the steady state: a significantly lower carbon dioxide concentration and a significantly higher oxygen concentration in the atmosphere.

The appearance of humans and human civilization, in turn, has exerted an extremely important impact on the cycling of carbon compounds (and many other elements). A period that significantly upset the carbon cycle began in the 19th century, together with the start of large-scale bituminous coal and lignite mining, followed by petroleum mining soon thereafter. Human combustion of fossil fuels (various types of coal, natural gas, and petrochemical products) now annually generates 10 times the amount of CO_2 released into the atmosphere by volcanic processes - these amounts already equal a few percent of the overall CO_2 quantities that are generated from normal processes of organic breakdown.

Consider that a one-meter-thick layer of peat (the type of fossil fuel that forms most quickly) takes at least 1000 years to accumulate. The deposits of bituminous coal we burn today were created back in the Cambrian (ca. 360-280 million years ago). The processes involved in the formation of petroleum have not yet been conclusively identified and their duration also remains unclear, but the prevailing conviction is that it is definitely longer than millions of years. If we look from the standpoint of how long well-developed human societies have existed so far, our consumption of fossil fuels reveals itself to be an extraordinarily fast process with tragically irreversible consequences.

Here we should likewise point out the impact of fossil deposits being used to synthesize polymers on the Earth's carbon cycle: this process significantly alters the circulation of carbon compounds in nature, leading to the accumulation of essentially non-degradable polymer wastes in amounts that are perhaps relatively small (when compared to the overall amounts of coal and petroleum that get mined) but nevertheless very problematic.

These and other factors are triggering a further shift, likely an unfavorable one, in the steady state. Mankind therefore must begin making efforts to curb the pace of coal and petroleum consumption, while at the same time accelerating processes that bring the circulation of carbon compounds "full circle."

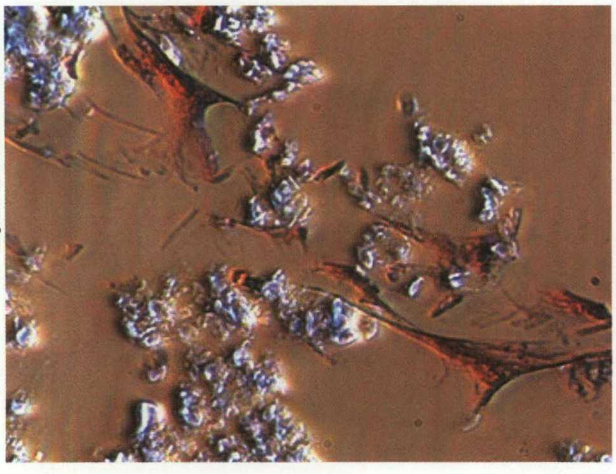
Capping consumption

Curbing growth in global coal and petroleum consumption will be extraordinarily difficult. It would not be easy, after all, to persuade the residents of rapidly developing countries like China and India that the standard of living enjoyed in the US, Japan, and developed European countries (associated with high consumption) will remain out of reach for them. As a result, efforts seeking to find effective renewable fuel sources - such as the production of ethanol from sugarcane or maize - have been underway for years now. But on the other hand, by occupying significant areas of land such crops encourage deforestation and pose competition for food crop farming.

In this situation, nuclear energy might seem like the only answer. However, expectations for the development of thermonuclear power plants that do not generate radioactive wastes have so far not come true. Even more fundamentally, we cannot forget that these processes also consume nonrenewable resources that are unevenly distributed in the world.

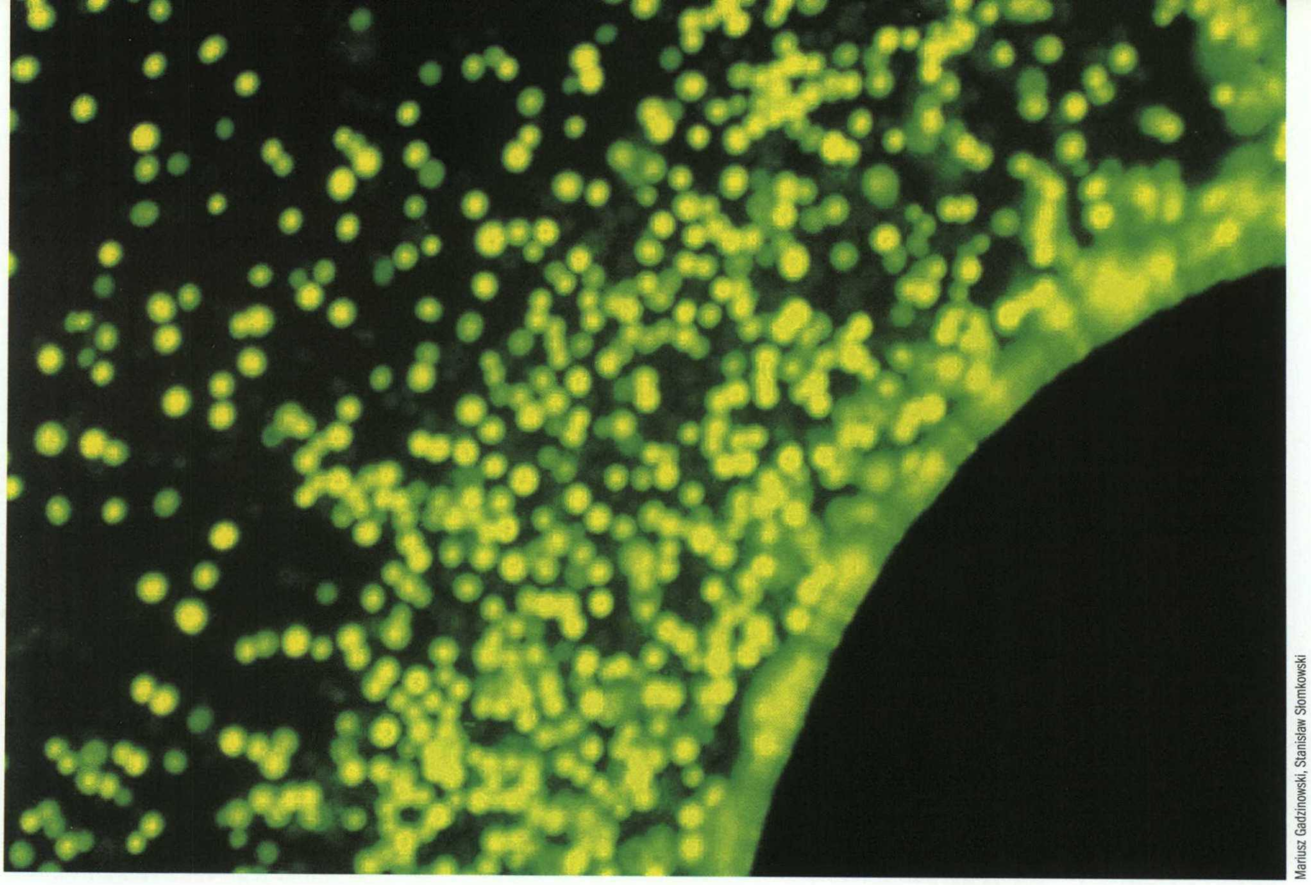
So how might the natural carbon cycle be brought back into better balance? One promising possibility that merits consideration is the use of simple organisms to quickly bind CO_2 and generate fuels and materials for use in synthesizing polymers. According to current estimates, the energy self-reliance of the United States could be ensured by cyanobacteria reactors - producing sucrose later fermented into ethanol - covering a surface area of just 115 x 115 km.

Moreover, the raw building-blocks used in such fuel biosynthesis methods based on alcoholic fermentation



Małgorzata Lewandowska-Szumieł, Piotr Woźniak

Osteoblasts (bone-forming cells) in a scaffold made of biodegradable and biocompatible polymer


Mariusz Gadzinowski, Stanisław Słomkowski

Polymer microspheres – fluorescent micromolecules made of biodegradable polymers, used as markers in biological research and also as drug-delivery mechanisms

can also be used in other types of fermentation, leading to the production of lactic acid. Lactic acid, in turn, can be used in producing polylactide, a biodegradable aliphatic polyester. When composted, polylactide takes just several weeks or months to degrade, after which it is reincorporated into the natural carbon cycle.

Biodegradable polymers

Nevertheless, polylactide is not yet being produced on a large scale. The reason for this lies in its price, which is now unfortunately about eight times higher than the price of polymers mass-produced from petrochemical components. However, research work now underway can be expected to deliver new technologies and bring polylactide prices down significantly. One of the world's best teams working on this avenue of research is based at the Center of Molecular and Macromolecular Studies of the Polish Academy of Sciences (including Stanisław Penczek, Andrzej Duda, Przemysław Kubisa, Tadeusz Biela, Stanisław Słomkowski, Andrzej Gałęski, Ewa Piórkowska). Our group studies the mechanisms of lactide polymerization, the synthesis of polylactides differing in terms of their stereochemical structure and macromolecule morphology, and the processes for their production, opening up the possibility of eventually developing an original Polish technology for polylactide synthesis.

In view of their biodegradability, certain biodegradable polymers made from such natural components have already found important applications in medicine. Because aliphatic polyesters, including polyactides, degrade into non-toxic products (at least if not present in excessive local concentrations) and can be incorporated into natural metabolic cycles, such polymers are being used as components in creating nano- and micro-devices for controlled drug delivery and in developing scaffolds for use in tissue engineering. Especially intense work is now underway on obtaining new bone tissue by introducing bone-forming osteoblast cells collected from a patient into a biodegradable scaffold made of such materials. Depending on the length of the polymer chains and their structure (polymer molecules frequently contain not just polyactide units but also fragments of other polymers), the speed at which these structures degrade (ranging from several weeks to several years) can be controlled and tailored to meet specific applications.

It is hard to anticipate how quickly this field of polymers made from renewable components will develop. There are many significant factors involved, involving not just the need for further scientific advancements but also politics and economics. However, the future undoubtedly belongs to such polymers. Mankind is nowadays harnessing the planet's existing resources at far too rapid a pace, and must pay greater attention to processes and technologies that enable their regeneration. ■

Further reading:

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