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COUNCIL FOR TECHNOLOGICAL SOVEREIGNTY

Discussion Paper

Bio-based Materials

and their Significance for Technological Sovereignty

Council for Technological Sovereignty

Introduction

In our position paper "Materials Research" (February 2025), we highlighted the central role of this research area in the development of new technologies and products, as well as its resulting importance for addressing global challenges. By developing novel materials with new properties, materials research lays the foundation for innovations and further developments in various industries and research disciplines. In the wake of increasing geopolitical tensions, its relevance is further underscored by its potential to reduce dependency on (raw) material imports - through the development of suitable substitutes, improving the recyclability of materials, and the products made from them.

This impulse paper supplements the "Materials research" position paper with a special focus on bio-based materials. Materials derived from nature or produced through microbial biosynthesis open up new opportunities to reduce the use of fossil raw materials and promote more independent, sustainable production in various sectors.[1] Biotechnological processes have the potential to supplement or completely replace traditional chemical production processes. In an increasingly globalised and resource-scarce environment, bio-based materials offer opportunities for a more sustainable economy, a more independent and resilient industry and thus a promising way to strengthen technological sovereignty. The use and development of bio-based materials spans a wide range of industries and applications - from packaging and textiles to building materials and plastics. However, in order to exploit the full potential of bio-based materials, it is necessary to take advantage of the opportunities offered by the ongoing digitalisation and automation of production processes. Technologies such as digital twins and AI methods[2] can play a decisive role here. In order to establish sustainable bioeconomic production, it is necessary to address not only research and development but also scalability in production, market implementation, and the political framework conditions.[3] Currently, these aspects are being shaped on an international level.[4]

BIOLOGICAL AND BIO-BASED MATERIALS

To avoid misunderstandings, a distinction is made here between **biological materials** or natural substances, such as grown wood or cotton, and **bio-based materials.** In line with the explanation provided by the Agency for Renewable Resources (FNR) on the subject of bioplastics, we use the adjective "biobased" in this text to refer to materials and products that have been manufactured to a significant extent or entirely from renewable raw materials" (https://biowerkstoffe.fnr.de/fileadmin/Projekte/2024/Biowerkstoff/BioKS-10-Punkte-2024.pdf). See also the European standard EN 16640 " Biobased products - Determination of the biobased carbon content of products using the radiocarbon method ".

BIOTECHNOLOGY

The term **biotechnology** refers to processes as defined by the OECD: according to this definition, biotechnology is "the application of science and technology to living organisms and their components and products with the aim of modifying or utilising them for the production of goods, services and knowledge" (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Biotechnology)

BIOCATALYSTS

Biocatalysts are molecules that enable biochemical reactions in living organisms. Most biocatalysts are proteins, known as enzymes, which are increasingly being used in isolated form - *in vitro* - in products and production processes across all industries.

BIOMANUFACTURING

Biomanufacturing is the use of biological systems, including plants and microbes such as bacteria, yeast and algae, or their enzymes and molecular components, to manufacture products on a relevant commercial scale.

Bio-based materials: properties and processing

Products from bio-based production can either replace those from fossil sources as "drop-in solutions" or be used to build complex structures due to their functionality.

Bio-based materials have properties such as chirality[5] and hierarchy sensitivity[6] , which distinguish them from conventional synthetic materials. Chirality occurs when the mirror image of an object cannot be made to coincide with the original by rotation. This property in nature and also the hierarchical arrangement of natural building blocks, which arise in nature through growth, give these materials unique functional properties such as selectivity, modularity, damage tolerance, adaptability and multifunctionality. These characteristics are also required in the development of new materials, particularly with regard to their integration into modern, adaptive systems. Research into adaptive systems, for example, is looking at how materials can be equipped with completely new adaptive functionality by integrating living cells.[7]

A better-known example of biotechnological innovations is the production of bio-based plastics, which can be produced using biotechnological processes such as the fermentation of industrial or residual materials (e.g. sugar or CO_2).[8] These materials not only offer a solution for reducing the consumption of fossil raw materials, but also enable a significant reduction in CO_2 emissions during production. There is also potential in the field of lightweight construction, for example, through the use of biotechnologically produced spider silk. These protein fibres combine a unique combination of material properties such as extreme elasticity and load-bearing capacity with antibacterial properties as well as biodegradability and recyclability and therefore represent an extremely promising material innovation if they can be produced on an industrial scale. Bio-based, biodegradable plastics such as polylactic acid are already being used in the packaging industry[9] . These bio-based materials offer an alternative to petroleum-based mass plastics. However, recyclability is not related to the carbon source: Both fossil-based and bio-based plastics may or may not be recyclable and/or degradable.

The use of biological processes in production is achieved through biotechnological processes that enable the direct use of microorganisms such as bacteria or yeasts for the production of chemicals and starting materials. Biocatalysis - i.e. enzymatic reactions - can be used to synthesise substances with high precision and in fewer production steps, which increases efficiency and reduces the environmental impact. For example, in the production of vitamin B2 through biocatalysis, the production costs, resource consumption, CO2 emissions, and waste materials are significantly lower than in chemical synthesis.[10] Biocatalytic processes therefore already play a central role in the circular economy and in the recycling of fossil raw materials. In the materials sector, the chemical industry has succeeded for the first time in producing bio-based aniline on a tonne scale, thus making this basic chemical available for a bio-based circular economy.[11]

Application of bio-based materials: markets and potentials

Industrial and consumer-oriented biotechnology often involves the use of genetic engineering to analyse and modify biological processes at the molecular level. Technical enzymes are frequently produced in genetically modified organisms. This enables the further development and production of bio-based products for both industrial and consumer applications. For example, companies are increasingly developing specialty chemicals and household products manufactured in this more sustainable and cost-effective manner. Enzyme-based aids derived from genetic engineering applications can also be used in the production of foods such as bread and baked goods.[12] Alternatively, optimized enzymes can replace one or multiple steps in chemical synthesis. The market potential of bio-based products is considered substantial by consulting firms[13] (seeFigure 1

Bio-based materials are currently used in the packaging, lightweight construction and textile industries in particular[14] . A large proportion of biological materials are processed in these sectors, with wood and paper products being the dominant share. In addition, biotechnologically developed and produced biocatalysts (e.g., enzymes) are used for processing or refining the products.

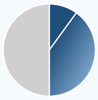
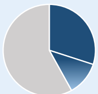
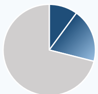
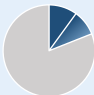
Enzymes such as amylases, cellulases, proteases, lipases and xylanases are used in the production of paper and pulp. These enzymes are usually tailor-made for specific purposes to make processes more efficient. In this way, they help save resources such as raw materials, energy, or time — for example, in paper recycling, where printer ink can be removed with the help of amylases. Enzymes for environmentally friendly and chlorine-free bleaching are considered one of the fastest-growing markets in industrial enzymes.

The use of bio-based plastics in the packaging industry is experiencing strong growth, which is expected to continue in the coming years. Bio-based plastics, produced from renewable raw materials such as starch, cellulose, or lactic acid, offer significant advantages compared to conventional petroleum-based plastics. They can substantially reduce the demand for fossil resources and contribute to lowering CO_2 emissions. Research is also currently underway on combining natural fibres with plastics to develop innovative materials[15].

Another important area is the production of biogas and biofuels, which are also increasingly being used to produce chemicals and plastics.

In the textile industry, the biotechnological/enzymatic processing of natural materials such as cotton or wool and, in particular, biotechnologically produced materials such as protein fibres, represents a promising approach for drastically reducing the consumption of water and chemicals. Here too, biocatalysts are used to, for example, lower processing temperatures, thereby making production more environmentally friendly and energy-efficient.

Bio-based materials inspired by nature can become a key component of a future circular economy (seeFigure 2). Establishing such a circular economy requires a sustainable connection between the biosphere and the technosphere, in which biotechnology plays a crucial role. This connection underscores the projected importance of biotechnology, including synthetic biology, for technological sovereignty.

	Market share in 2040	Potential 2040 revenue ($ billion)	Example companies
Alternative proteins *Cultured meat; microbial proteins (e.g. mycoproteins)¹*	 10-50 %	24-390	Upside Foods, Vow
Agricultural biotechnology *Genetically modified animals and crops that help disease resistance, yield, etc; selective breeding of crops and animals through genetic markers*	 30-42 %	170-230	Bayer Crop Science, Syngenta
Consumer products and services *Personalized genetic insights; personalized beauty, health, and wellness products (e.g. DNA-based diets, personalized skincare); microbiome-based products (e.g. probiotics)*	 10-29 %	71-170	Novonesis, IFF, Givaudan, PROVEN Skincare
Biomaterials and biochemicals *Bioplastics (e.g. PHAs or polyhydroxyalkanoates); fermentation-based chemicals (e.g. ethanol; 1,4-butanediol; lactic acid); bio-based additives to food, feed (e.g. enzymes, probiotics); microbial crop protection*	 10-19 %	70-100	Danimer, Genomatica, Corbion, Dupont, Lanzatech, Avantium

[1] Cultured meat is produced by cultivating animal cells directly. Mycoproteins are plant-based proteins derived from a natural microfungus, *Fusarium venenatum*.

Figure 1: Segments of the non-medical biotechnology industry with market shares and potential revenues forecast by McKinsey.[16]

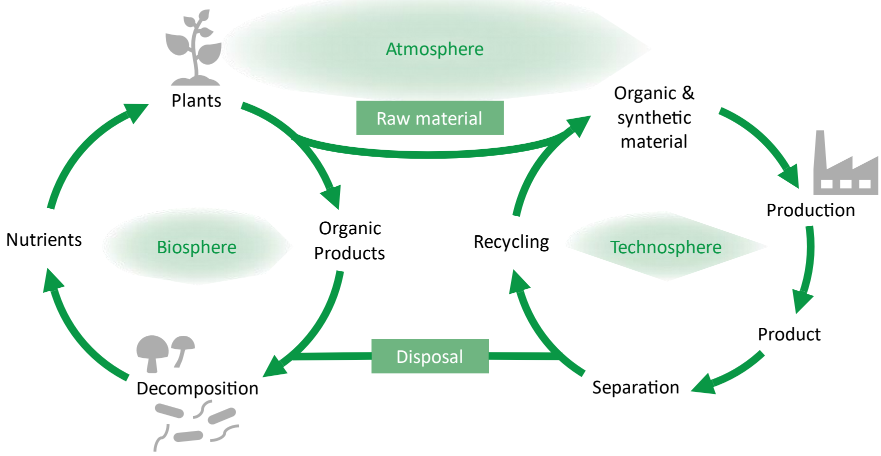


Figure 2: Bio-based circular economy. Beyond the illustration, there is potential for further recycling at every point in the cycle, for example through the reutilisation of by-products. Source: own illustration.

SIGNIFICANCE OF SYNTHETIC BIOLOGY FOR TECHNOLOGICAL SOVEREIGNTY

Synthetic biology is the deliberate design and optimization of biological systems through the application of engineering principles to genetic and biological processes, aiming to create new or improved functions.

This modern biotechnology holds the potential to develop and control biological systems. By precisely modifying genetic information and biological processes, new sustainable materials and production methods can be created that are less dependent on external resources. This strengthens economic and technological autonomy by enabling essential value chains to be established locally.

Moreover, synthetic biology opens up new opportunities in medicine, agriculture, and energy production by providing tailor-made solutions for specific challenges. Continuous research and development in this field can therefore play a crucial role in securing technological sovereignty and promoting sustainable innovations.

Challenges and opportunities for technological sovereignty in the field of bio-based materials

In order for bio-based materials to replace those derived from fossil sources in the future, research is needed at all key stages and transition points along the path to a circular bioeconomy.

Since working with living systems in the context of materials requires innovative production methods, product prices are currently still two to three times higher than those of conventional manufacturing processes. Therefore, the production process must be gradually optimized with regard to competitiveness in order to realize cost reduction potentials in production. For example, residues and/or by-products may occur during the production of bio-based materials that only become evident at larger production scales. Experts refer to this as the "*valley of death*"[17] when high technical risks during production scale-up coincide with significant plant construction costs. This also applies to the production of bio-based products. Reducing existing barriers can accelerate the development and establishment of new production methods.[18]

Access to novel materials and production methods is an important aspect of Germany's technological sovereignty. As a prerequisite for establishing production processes for biological materials on an industrial scale, metrics must be applied or newly developed to, for example, determine energy efficiency across the entire process chain and, in a further step, drive process optimization. This approach can increase the sustainability of production in the medium and long term. While biological materials are produced under mild reaction conditions (such as in aqueous solution at room or body temperature), industrial production often requires handling larger volumes and complex downstream processes. Managing large volumes during purification can be energy-intensive. Innovative energy-saving technologies and process optimizations can support increasing the sustainability of production.

Progress is also expected through the integration of digitalization into industrial production. The use of artificial intelligence and *in silico* simulations allows for better understanding and optimization of complex biological processes. The application of digital twins to model bioprocesses enables more precise prediction and control of production processes, as well as improvements in their efficiency and scalability.

For a successful transition from niche applications to mass-market suitability, biotechnological manufacturing methods for industrial-scale production must be developed. This requires optimizing production organisms, such as switching from batch processes—where the process is stopped after each production run, the product is "harvested," and the process is restarted—to continuous fermentation. Relevant research questions are currently being addressed in various projects. Additionally, the development and use of standardized modular systems for **biomanufacturing**, which are already established in other fields, could help reduce production costs.[19]

In certain industries, regulatory framework conditions also pose a challenge. For example, the EU Packaging Directive, which prohibits packaging without established recycling routes, complicates the use of innovative materials that may not be compatible with existing commercial recycling systems.[20]

To establish bio-based production on an industrial scale, dialogue with society is crucial in order to promote the acceptance of and demand for bio-based products. Real-world laboratories and accompanying research projects offer a platform for dialogue between research, industry and society, which could enable innovative solutions to reach the market more quickly.

Conclusion: Sustainability and technological sovereignty through research and production of bio-based materials and substances

Bio-based materials offer a promising foundation for more sustainable and resource-efficient production, as well as for reducing dependencies on raw material and material imports (see also Chapter 2.1 in the position paper Materials Research). Their application in areas such as packaging, lightweight construction, textiles, and chemical production represents a significant step towards a circular economy. At the same time, biotechnological processes can enable more efficient use of raw materials and energy, contributing to the reduction of greenhouse gas emissions.

For long-term technological sovereignty, it is crucial to advance the digitalization, scalability, and standardization of bio-based production processes while promoting competition and transparency in the market. Together with societal understanding of the production and use of bio-based materials, this can unlock the full potential and set the course for a sustainable future.

[1] https://www.bmwk.de/Redaktion/DE/Downloads/I/Industrielle-Biooekonomie/positionspapier-der-dialogplattform-industrielle-biookonomie-leitmarkt-biookonomie.pdf?__blob=publicationFile&v=7

[2] One example of such an AI-based tool is AlphaFold: https://alphafold.ebi.ac.uk/

[3] https://projekttraeger.dlr.de/sites/default/files/2025-09/documents/Position-Paper-Materials-Research_rat4ts.pdf

[4] https://commission.europa.eu/document/download/10017eb1-4722-4333-add2-e0ed18105a34_en and for the USA: https://www.whitehouse.gov/ostp/news-updates/2023/03/22/fact-sheet-biden-harris-administration-announces-new-bold-goals-and-

priorities-to-advance-american-biotechnology-and-biomanufacturing/ and https://commission.europa.eu/document/download/e6cd4328-673c-4e7a-8683-f63ffb2cf648_en?filename=Political%20Guidelines%202024-2029_EN.pdf and https://english.www.gov.cn/policies/policy-watch/202205/11/content_WS627b169ec6d

[5] Chirality: Enantiomers are stereoisomers of chemical compounds that are chemically identical; they therefore have the same molecular formula and the atoms are linked in the same way. The spatial structures of a pair of enantiomers relate to each other exactly like image and mirror image. The two enantiomers ("right-turning - left-turning") react differently in chemical reactions in which a chiral reference system is present and cause different effects in reactions in organic chemistry.

[6] Hierarchy sensitivity refers to the dependence of material properties on the structural organisation of the bio-based material at different length scales, from the molecular to the macroscopic level. This sensitivity reflects the complex interaction between the hierarchical structures that significantly influence the mechanical, thermal and functional properties of the materials. In addition, in plant growth, for example, all developmental steps are made possible by the fact that of the genes present in all cells of the organism, only very specific genes are activated following a precise temporal-spatial pattern. Such patterns of development are made possible by a hierarchy of control genes

[7] https://gepris.dfg.de/gepris/projekt/541299811?language=en, https://gepris.dfg.de/gepris/projekt/521156679

[8] https://www.covestro.com/press/de/weltweit-erste-pilotanlage-fuer-biobasiertes-anilin/

[9] https://ceresana.com/produkt/marktstudie-polymilchsaeure

[10] See also https://vaam.de/media/bs_birgit_hoff.pdf and

[11] https://www.fnr.de/presse/pressemitteilungen/archiv/archiv-nachricht/fortschritte-auf-dem-weg-zum-kommerziellen-biobasierten-anilin

[12] https://www.transgen.de/datenbank/lebensmittel/2094.brot-broetchen-backwaren.html

[13] McKinsey Global Institute, October 2024

[14] Data on the bioeconomy in Germany, nova-Institut GmbH, July 2019

[15] https://www.lbf.fraunhofer.de/en/competencies-researchdivisions/plastics/lightweight-sustainable-plastics.html

[16] Graphic (updated) based on: McKinsey Global Institute - "The next big arenas of competition" (October 2024)

[17] Navigating the Valley of Death: Perceptions of Industry and Academia on Production Platforms and Opportunities in Biotechnology -

[18] See also https://vaam.de/media/bs_birgit_hoff.pdf as well as https://pmc.ncbi.nlm.nih.gov/articles/PMC7693651/

[19] Jean-François Bobier, Tristan Cerisy, Anne-Douce Coulin, Crystal Bleecher, Victoria Sassoon, and Brentan Alexander (February 2024)

[20] There is an "innovation clause" for innovative packaging, but this only offers limited support for fundamental material innovations in the plastics sector. The European Commission is also planning to re-evaluate bio-based plastics.

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Members of the Council for Technological Sovereignty
Dr. Viola Bronsema
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Prof. Dr. Andreas Tünnermann

Lead authors of this paper
Viola Bronsema

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Contact

DLR Project Management Agency

Society, Innovation, Technology
Strategies for Key Enabling Technologies
pt-ts@dlr.de

DLR Projektträger