Federal Ministry
of Education
and Research

Federal Ministry
of Food
and Agriculture

Bioeconomy in Germany

Opportunities for a bio-based and sustainable future

Foreword

Sustainability and climate action are the key issues of the 21st century. Dwindling resources, declining biodiversity and the effects of climate change present us with major challenges while a growing world population needs food and economic prosperity.

To meet these global challenges, we must fundamentally change the way we run our economy and the way we live. Industry and society have already started to change, and this transformation is gaining momentum, with sustainable and climate-neutral business models based on renewable resources becoming increasingly common.

The bioeconomy views itself as a sustainable economic concept which develops products and processes using biological resources, know-how and innovative technologies. Food, materials and energy are produced from renewable resources. A bio-based economy promotes a sustainable and climate-neutral way of running our economy which intelligently reconciles ecology and economy and is aligned with natural material cycles.

By international comparison, Germany is a pioneer of the bioeconomy, with the German Federal Government having supported the path towards a bio-based economy with strategies and funding programmes since the 1990s. The new National Bioeconomy Strategy was published in January 2020. It provides a framework for the sustainable development and utilisation of biological resources and for environmentally friendly, natural production processes across all economic sectors. Moving towards a circular bioeconomy is part of Germany's contribution to meeting the UN Sustainable Development Goals and sets the course for the technologies and jobs of the future.

The Federal Ministry of Education and Research (BMBF) and the Federal Ministry of Food and Agriculture (BMEL) are leading the National Bioeconomy Strategy. This brochure provides an overview of Germany's efforts to create a sustainable bioeconomy according to key sectors, concepts, resources and production processes and presents some promising research initiatives. It provides an insight into current innovation processes across various industries. Many of the research and development projects described are funded by the BMBF and BMEL.

This illustrates the diversity of approaches, shows where bio-based industrial activities are already being practiced, how they have become part of our everyday lives, and how the bioeconomy can become a building block of a sustainable economic system.

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Bioeconomy – an introduction

Scarce fossil resources, climate change and a growing world population: These are challenges that require sustainable, resource-efficient and climate-neutral strategies in order to secure our long-term prosperity. The bioeconomy offers the opportunity to reconcile economic growth with nature conservation and environmental protection. Germany is an international leader in the field of technology and research.

A growing world population, dwindling resources, declining biodiversity and the effects of climate change present us with existential challenges. While our industry still heavily relies on fossil resources such as petroleum and natural gas, these resources are finite and drive global warming. The raw materials base of our industries and the way we operate need to change in order to overcome the current global challenges. But how can we conserve resources, preserve biodiversity – and thus our own livelihood – in the long term while securing our standard of living?

One possible contribution towards changing our economy to become more sustainable is the switch to a bioeconomy, an economy based on biological resources and processes. The concept of the bioeconomy builds on the potential of living organisms such as plants, animals and microorganisms. The big goal for the future is to create a sustainable way of living and operating that cleverly reconciles ecology and the economy.

Innovative access to biological systems

The German Federal Government defines the bioeconomy as the production, exploitation and use of biological resources, processes and systems to provide products, processes and services in all economic sectors within the framework of a sustainable economic system.

While humans have been using plants, animals and microorganisms for thousands of years, the modern bioeconomy is based on the particular concept of a knowledge-based approach to biological systems that draws on the rapidly growing wealth of research findings and developments, and benefits from these biological systems. The bioeconomy offers a new view of nature's achievements, abilities and its diversity, as well as of the variety and cultivation of renewable resources and the economic and creative use of modern technologies. Bio-based resources and processes not only provide solutions that help reduce the use of fossil resources, they also enable us to translate scientific and technological advances into innovative applications that go far beyond simply replacing petroleum, and create added value.

Using biological resources

Bioeconomy means that biogenic raw materials are produced by agriculture and forestry, marine and water management including fishery and aquaculture, or with the help of microorganisms *(see chapter The resources of the bioeconomy)*. A special focus lies on recycling and utilising organic residues and waste materials in order to make sensible use of previously discarded by-products of production. This is called coupled use. Even water and carbon dioxide may be used for bio-based processes. The bioeconomy is not just about renewable raw materials, however: It is also about bio-based processes performed by microorganisms, animal and plant cells and their components, such as enzymes..

"Bioeconomy refers to the production, exploitation and use of biological resources, processes and systems to provide products, processes and services in all economic sectors within the framework of a sustainable economic system."

Definition of the German Federal Government

Sustainable circular economy

Biomass, the key raw material of the bioeconomy, is more than just a renewable resource. Compared to other forms of raw materials, it is particularly suitable for sustainable circular use. In nature, biological resources are integrated into material cycles such as the carbon cycle or the nitrogen cycle. Circular processes ensure a balance between the use and regeneration of these resources. The bioeconomy is modelled on these natural material cycles.

Its goal is a circular economy which produces a minimum of waste and residue through the efficient use of biological resources along the entire value chain. Ideally, the amount of carbon dioxide produced should not exceed the amount that was removed from the atmosphere during the growth phase of photosynthesis-performing plants, algae or bacteria. This is one of the building blocks of a climate-neutral economy *(see chapter Circular bioproduction)*.

Biological resources and bio-based processes or products can offer a climate- and resource-friendly alternative to fossil-based raw materials and products. This is how the bioeconomy can make an important contribution towards attaining the United Nations Sustainable Development Goals adopted in 2015 *(see chapter Aiming for a sustainable bioeconomy)*. The economic, ecological and social dimensions of sustainability must be equally considered to recognise conflicts of interest at an early stage and to carefully weigh them against each other to find the most sustainable solution in each case.

Key indicators of the German bioeconomy*

4.4 million people were employed in the bioeconomy in 2017. That is 10% of the workforce. The manufacturing industry (e.g. food industry) and the hospitality industry account for the largest share.

165 billion euros were added in gross value by the biomass-based economy in 2017. Depending on the modelling approach, this corresponds to up to 265 billion euros.

* Pilot Report on the Monitoring of the German Bioeconomy (2020)

Milestones of bioeconomy policy

Internationally, Germany is leading the way towards a bioeconomy and is a pioneer of supporting research. The German Federal Government put the bioeconomy on its political agenda as early as 2010 when the **National Research Strategy BioEconomy 2030** was launched at the initiative of the Federal Ministry of Education and Research (BMBF). The programme provided 2.4 billion euros for bioeconomy research, which paved the way for the **National Bioeconomy Policy Strategy** of 2013, which was devised by the Federal Ministry of Food and Agriculture (BMEL).

The **National Bioeconomy Strategy**, which was published by the Federal Cabinet in January 2020, was another milestone. This government strategy is to prepare the ground for Germany's ongoing pioneering role in the development of the bioeconomy, and for creating the technologies and jobs of the future *(see box p. 5)*. The Bioeconomy Council has been providing additional support by advising the Federal Government since 2009.

Currently in its third term (2021 to 2023), the Bioeconomy Council is composed of experts from various disciplines in science and industry. It prepares recommendations for the development of future research priorities and advocates dialogue with all stakeholders and social participation *(see chapter The social dialogue)*.

The bioeconomy at a Federal State level

Some Federal States have started funding research into the bioeconomy, not least thanks to the broad political support from the Federal Government. In 2013, **Baden-Württemberg** was one of the first Federal States to have its own bioeconomy research strategy and a federal state research programme. In June 2019, the government of Baden-Württemberg adopted an interdepartmental strategy entitled State Strategy for a Sustainable Bioeconomy. The state government has earmarked a total of 50 million euros for the implementation of the strategy's measures between 2020 and 2024.

In 2015, **Bavaria** was the first Federal State to convene its own Bioeconomy Expert Council, which was

National Bioeconomy Strategy

The National Bioeconomy Strategy published in January 2020 defines the framework for the sustainable development and use of biological resources and for environmentally and nature-friendly production processes in all sectors of the economy. This overall strategy integrates the bioeconomy activities of the individual Federal Ministries and sets the course for their further development. At the same time, the German Federal Government is aligning its bioeconomy policy even more closely with the overarching goal of sustainable and climate-neutral development.

The Federal Ministry of Education and Research (BMBF) and the Federal Ministry of Food and Agriculture (BMEL) are leading the bioeconomy strategy. Moving towards a bioeconomy is part of Germany's contribution to attaining theSustainable Development Goals and will help secure Germany's leading position in the markets of the future.

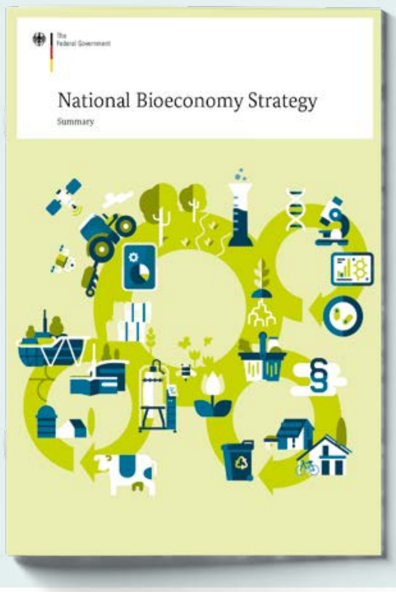
Two overarching guidelines underpin the objectives and actions set out in the National Bioeconomy Strategy.

The first guideline highlights biological knowledge and advanced technology as the pillars of a future-proof, sustainable and climate-neutral economy. The second guideline refers to the economy's raw materials base that is set to be based on biogenic resources and become part of a circular economy.

The Federal Government's National Bioeconomy Strategy addresses a broad range of objectives for different parts of society and all industries, which can be summarised in six common strategic goals:

- Develop bioeconomy solutions for the Agenda 2030 for Sustainable Development
- Recognise and harness the potential of the bioeconomy within ecological boundaries
- Enhance and apply biological knowledge
- Establish a sustainable raw material base for industry
- Promote Germany as the leading location for innovation in the bioeconomy
- Involve society in the bioeconomy and strengthen national and international collaboration

For each of these strategic goals, specific implementation objectives have been formulated in the context of research funding, the pertinent framework conditions and cross-cutting instruments.



followed by the new Bavarian Bioeconomy Strategy in November 2020. The strategy lists eight key goals and 50 concrete actions to create a circular, sustainable bioeconomy.

North Rhine-Westphalia adopted its own bioeconomy strategy as early as 2013. The research strategy is coordinated by the interdisciplinary Bioeconomy Science Center (BioSC) with the involvement of the universities of Aachen, Bonn and Düsseldorf, as well as the Forschungszentrum Jülich.

Central Germany has also developed into a bioeconomy hub: In October 2012, the Fraunhofer-Gesellschaft inaugurated a biorefinery research centre for chemical-biotechnological processes (CBP) in Leuna,

The bioeconomy research landscape in Germany

Germany's bioeconomy research landscape has a broad base: A wide range of bioeconomy activities are carried out at 73 universities as well as 64 universities of applied sciences. In addition, research is carried out at 156 non-university institutes such as those of the Fraunhofer-Gesellschaft, the Max Planck Society, the Leibniz Association and the Helmholtz Association as well as 40 departmental research institutions. Research activities in the bioeconomy are not limited to one discipline, however, but include agricultural science, life sciences, mechanical and process plant engineering, and aspects of the social sciences. The number of university programmes covering the bioeconomy and sustainability is growing steadily *(see chapter Bioeconomy careers)*.

a city with a long tradition in the chemical industry. The Federal State of **Saxony-Anhalt** and the German Federal Government have provided a total of around 50 million euros for setting up the CBP. From 2012 to 2017, the region received 40 million euros in funding from the BMBF through the BioEconomy Leading-Edge Cluster which has led to the formation of BioEconomy e.V. This innovation cluster has secured funding from the state of Saxony-Anhalt until 2026. The BioEconomy cluster is connected far beyond the states of Saxony and Saxony-Anhalt.

The bioeconomy – an economic factor

The bioeconomy is a cross-sectoral industry: It includes all economic sectors and related services that produce, process, use and trade in biological resources such as plants, animals and microorganisms and their products. These sectors comprise agriculture and forestry, chemistry and pharmacy, the food industry, industrial biotechnology, cosmetics as well as the paper and textile industries in particular. Some of them, such as agriculture, forestry and the food industry, are almost completely bio-based. Others, such as the chemical and consumer goods industries, only partly rely on biological resources and bio-based processes. This makes determining the economic key indicators of the bioeconomy a challenge. These figures do exist, though, thanks to the German Bioeconomy Monitoring, a joint project by the three Federal Ministries of Research, Agriculture, and Economics. More than a dozen research institutions have joined forces to develop tools to measure and evaluate a bio-based economy. According to the 2020 Pilot Report on the Monitoring of the German Bioeconomy, in 2017, the German bioeconomy employed around 4.4 million people, or around 10% of the German workforce.

Depending on the definition of the bioeconomy and on the modelling approach, the gross value added by the bioeconomy in 2017 was between 165 billion and 265 billion euros. This is almost 6% of Germany's gross domestic product. Traditional sectors such as agriculture, forestry, fishery and aquaculture, wooden furniture, paper manufacturing as well as food, feed and beverage production and the hospitality industry account for more than two thirds of the value added. At the time of the survey, sectors that are attributable to the so-called industrial bioeconomy were still generating a comparatively small share of the bioeconomy. These sectors include bio-based textiles, chemicals, pharmaceuticals and plastics.

A contribution to sustainable innovation

The bioeconomy represents a comprehensive approach, both in terms of its objectives and in terms of its scope. The research side is concerned with the natural sciences, engineering, social sciences and the humanities, and extends to applications that affect many areas of life and almost the entire economy. This makes the bioeconomy more than a technical or economic programme. It is about the use of biological knowledge and biogenic resources in the interest of sustainability. Achieving this will require new forms of interdisciplinary cooperation and new types of value creation networks, and will also open up interesting career prospects *(see chapter Bioeconomy careers).*

Aiming for a sustainable bioeconomy

A bio-based economy can make an important contribution to attaining the United Nations Sustainable Development Goals (SDGs). The National Bioeconomy Strategy addresses eleven SDGs in particular in order to support sustainable development. This requires a holistic view and international cooperation because a sustainable bioeconomy can only work if it addresses global challenges and markets in an international framework.

Forestry has long been following the principle of sustainability, which stipulates that the amount of trees felled may not exceed new growth. Hans Carl von Carlowitz postulated this principle back in 1713, laying the foundation for sustainable forestry.

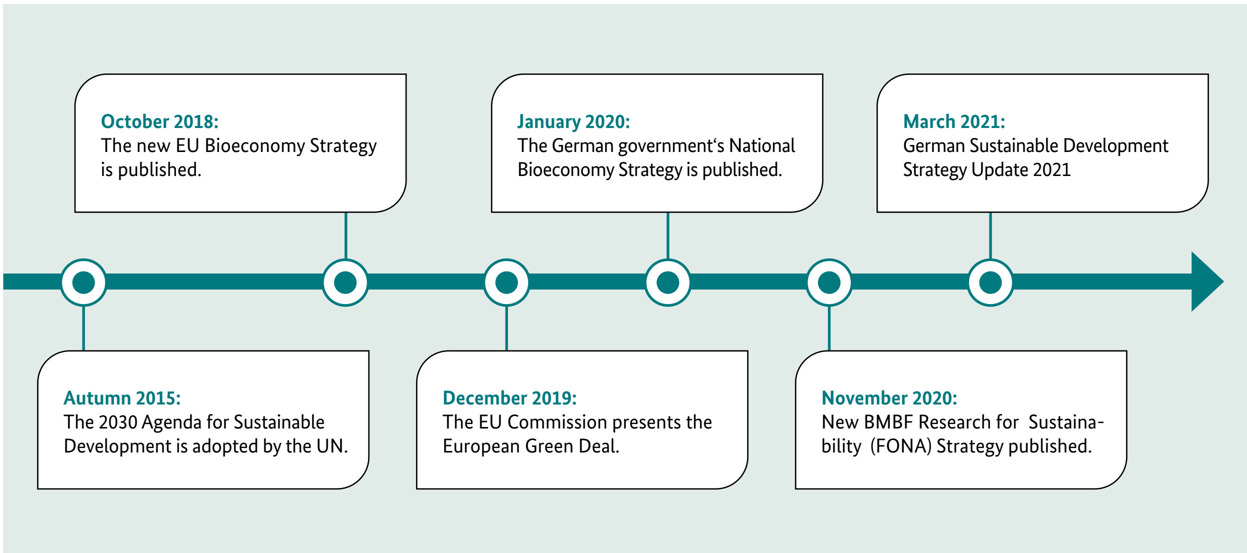
In 1987, the Brundtland Report then created the basis for the much broader concept of sustainable development as a guiding political principle that is used today. “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Sustainability thus means responsibility for the future.

There are three mutually dependent dimensions of sustainability: the economic, the ecological and the social dimension. To identify conflicts of objectives early on and to carefully weigh up all options in order to find the most sustainable solution, all of these dimensions must be taken into consideration. It is important to note that sustainable development can only be achieved if environmental, economic and social goals are implemented together and equitably. Furthermore, the preservation of global natural resources and respect for the limits of our planet as well as a life in dignity are mandatory.

In pursuit of the UN Sustainable Development Goals

Feeding a rapidly growing world population, fighting climate change and the loss of biodiversity, an economic system that is often still too resource-intensive: In 2015, the United Nations (UN) adopted the 2030 Agenda for Sustainable Development in response to the increasingly complex global challenges of our time. With the 2030 Agenda, the international community has set itself 17 Sustainable Development Goals (SDGs) with 169 subgoals. The UN Sustainable Development Goals comprise an economically efficient, socially just and ecologically sound development. All states are called upon to implement the Agenda’s universal standards by 2030.

A range of policy initiatives at national and EU levels have been aligned with the 2030 Agenda: The German Federal Government has launched Germany’s Sustainable Development Strategy to contribute to the swift and far-reaching implementation of the 17 UN Sustainable Development Goals. The High-Tech Strategy 2025, an overarching national innovation strategy, sets out a specific field of action and defines various missions to foster sustainability. The new Research for Sustainability (FONA) strategy published by the Federal Ministry of Education and Research (BMBF) in 2020 is also closely aligned with the SDGs. In 2018, the European Union presented its new Bioeconomy Strategy. A year later, the EU Commission launched the European Green Deal, a



Sustainability and Bioeconomy on the political agenda: Important milestones since 2015

The German government believes that the bioeconomy can help to meet eleven of the 17 UN Sustainable Development Goals.

transformative policy project to make Europe the first sustainable, greenhouse gas-neutral continent by 2050. The European Green Deal is a sustainable growth strategy that aims to decouple economic growth from the consumption of resources and environmental pollution by creating a climate-neutral, resource-efficient and competitive economy.

The National Bioeconomy Strategy and the SDGs

With the 2020 National Bioeconomy Strategy, the Federal Government has aligned its bioeconomy policy even more closely with the overarching goal of sustainable and climate-neutral development *(see chapter Introduction)*. The guidelines and goals of the strategy are based on the UN Sustainable Development Goals. Of the 17 SDGs, eleven have been identified to be instrumental for establishing a bioeconomy by the German Federal Government.

The top priority is always food security (**SDG 2: Zero Hunger**). The bioeconomy provides healthy food and biopharmaceuticals (**SDG 3: Good Health and Well-being**). Sustainable, bio-based products are a desirable alternative to petroleum-based goods (**SDG 12: Responsible Consumption and Production**). Furthermore, bioeconomic innovations enable novel and resource-efficient processes and products across all industries (**SDG 9: Industry, Innovation and Infrastructure**). Their natural properties make biogenic raw materials particularly suited to being managed in cycles and used in cascades. At the very end of the value chain, biomass can still provide energy (**SDG 7: Affordable and Clean Energy**).

A sustainable bioeconomy relies on functioning ecosystems and biodiversity and contributes to preserving ecosystem services. Life in the water and on land are elementary for the bioeconomy (**SDGs 14 and 15**). Both life on land and the cultivation of biomass rely on healthy soil and water. While agricultural production should save resources where possible, the bioeconomy offers solutions for water treatment (**SDG 6: Clean Water and Sanitation**).

Biomass binds carbon, and plant growth removes carbon dioxide from the atmosphere. In the future, agriculture and forestry will pay more attention to their function as sinks for greenhouse gas. In industrial production, the bioeconomy contributes to saving greenhouse gas emissions by substituting fossil raw materials and employing resource-saving processes (**SDG 13: Climate Action**).

The bioeconomy extends across all industries and enables forms of value creation which have been adapted to regional conditions, both in rural areas and in the urban bioeconomy (**SDG 11: Sustainable Cities and Communities**). The overarching goal is to reconcile ecology and economy and to support the transformation to a sustainable economy (**SDG 8: Decent Work and Economic Growth**).

These SDGs are interconnected, with some goals depending on others being met, while others may be in competition with each other. These interconnections and challenges are the focus of the National Bioeconomy Strategy.

The search for holistic approaches

Transforming our economy into a bioeconomy is a complex process. Which developments can help meet this goal? And where do we have to leave the trodden paths because they haven proven to be unsustainable? To answer these questions, we need comprehensive and reliable data on the use of natural resources and the associated effects.

The complexity of the challenges that society faces and the sometimes contradictory ways of solving them can lead to conflicts of interest. To develop viable and sustainable solutions through a bio-based economy, we need to view systems – from the cell to the organism to production systems and ecosystems – in a holistic manner. Systemic thinking and holistic approaches will provide the scientific basis needed to identify and alleviate any conflicts.

To monitor, measure and evaluate the transformation towards a bio-based economy, the German Federal Government has been supporting the establishment of a comprehensive bioeconomy monitoring system since 2016. The idea is to continuously refine the system to provide the information which will serve as a basis for decision-making, political action and public discourse *(see box p. 12)*.

The shift towards a bio-based economy is not only a technological and economic transformation, but also a societal one. A multitude of factors must be taken into consideration at both a regional and a global level. Bioeconomy research has to create a link between biological knowledge and technological solutions on the one hand, and research on the social and ecological systems providing the framework for the bioeconomy on the other.

The BMBF's Bioeconomy as Societal Change programme focusses on researching the social, political and economic science behind the transformation towards a bioeconomy. The BMBF has created close ties between a concept for the promotion of young scientists and entrepreneurs in the field of the bioeconomy and the Sustainability Agenda which is anchored in the National Bioeconomy Strategy *(see chapter Bioeconomy careers)*.

The new Bioeconomy Council

In the autumn of 2020, the third Bioeconomy Council took up its work of advising the Federal Government for an initial period of three years, with a particular focus on the implementation of the National Bioeconomy Strategy. The 20 members' combined expertise covers all aspects of the bioeconomy in the areas of business, science and society. In addition to drafting statements, the Bioeconomy Council is also tasked with promoting public debate *(see chapter The social dialogue)* in order to address any conflicts arising during the implementation of the sustainability goals of the bioeconomy. The Council also drafts recommendations for the implementation of the National Bioeconomy Strategy and regularly updates these recommendations during the term of the strategy programme.

International cooperation

More and more countries consider the bioeconomy as a building block of a sustainable economic system with growing political importance. According to the 2020 Global Bioeconomy Policy Report, 19 countries worldwide have adopted a dedicated bioeconomy strategy, and a similar number are working on a con-

Global bioeconomy strategies

The Global Bioeconomy Policy Report is written and published by the International Advisory Council on Global Bioeconomy (IACGB) and provides an overview of global bioeconomy policies. The Report identified 19 countries or macro-regions that had launched dedicated bioeconomy strategies in 2020. These are, in alphabetical order: Austria, Costa Rica, East Africa, the European Union, Finland, France, Germany, Great Britain, Ireland, Italy, Japan, Latvia, Malaysia, the Nordic countries, Norway, South Africa, Spain, Thailand and the USA. About 60 countries worldwide have launched policies with relevance for the bioeconomy.

Monitoring: tracking the ecological footprints of the German bioeconomy

Monitoring is the systematic recording, measuring and observing of a process with the use of suitable tools. As we move towards a sustainable bioeconomy, monitoring data provides an important basis for making decisions and for evaluating and controlling change, as well as for highlighting both progress and undesirable developments. This is why, in 2016, the German Federal Ministries of Research, Economics, and Agriculture launched a joint **bioeconomy monitoring** programme.

The research project Systemic Monitoring and Modelling of the Bioeconomy, or SYMOBIO for short, is funded by the BMBF. The first pilot report was presented in 2020. This monitoring programme records comprehensive data on the material flow of bio-based industries (e.g. grain, fish, wood) and identifies economic key indicators and trends, also taking into account international interconnections.

Identifying the indicators that can be used to determine the extent to which specific Sustainable Development Goals are being achieved is one of the challenges in establishing bioeconomy monitoring. To help with monitoring the bioeconomy, so-called resource and climate footprints were calculated, which identify the amount of natural resources consumed by humans and the effects of the bioeconomy on the climate and the environment.

In 2015, Germany used far more agricultural land worldwide (50 million hectares) for production than the agricultural land actually available within Germany (17 million hectares). The climate footprint of consumption of bio-based products in Germany is just under one fifth (18%) of the country's total climate footprint. The consumption of agricultural products accounts for the largest share of greenhouse gas emissions in the bioeconomy. To refine bioeconomy monitoring, the BMBF has been funding the follow-up project SYMOBIO 2.0 since 2022. SYMBIO 2.0 aims to take even greater account of climate and biodiversity effects as well as developments in agriculture.

cept *(see box p.11)*. The programmes differ from country to country, depending on the resources available and the political, social and technological conditions.

While a bioeconomy must always be implemented at a regional level, it is also clear that in view of the global nature of the challenges, markets and trade relations, we cannot do without international cooperation in order to successfully create a sustainable bioeconomy. In recent years, the German Federal Government has been instrumental in enhancing this cooperation.

The National Bioeconomy Strategy is set to promote these types of cooperation projects to enable mutual learning and joint research. At a European level, the European Research Area (ERA) Net initiative plays an important role in research funding. Various Federal Ministries, including the BMBF and the BMEL, contribute to funding the German partners of European research networks.

The European Commission is also strongly committed to partnerships with companies from the bio-based economy, for instance through the public-private partnership Bio-based Industries Joint Undertaking (BBI JU), which was launched in 2014. The BBI JU is a collaboration platform for public research institutions, small and medium-sized enterprises and industrial corporations along the entire value chain for the promotion of a speedy launch of sustainable innovations. In future, the initiative will be continued through the Circular Bio-based Europe Joint Undertaking.

With the Bioeconomy International funding programme, the BMBF supports mostly bilateral collaborations between German research institutions and non-European partners. These collaborations provide models for international research and development projects with non-EU countries. Previous partner countries for this initiative included Vietnam, Brazil, Canada, Russia, China and Chile.

Global Bioeconomy Summit

Since its debut in 2015, the Global Bioeconomy Summit (GBS) has become the most important international forum on the bioeconomy. The conference was initiated by the Bioeconomy Council 2012–2019 and is funded by the German Federal Government. The high-level summit stretches over several days and has become established as a source of inspiration for the development of the global bioeconomy. In 2020, the third GBS attracted bioeconomy, innovation and sustainability experts from all over the world. The event is now organised and hosted by the International Advisory Council on Global Bioeconomy (IACGB), an international think tank of bioeconomy experts.

The resources of the bioeconomy

Plants, animals and microorganisms are the sources of raw materials for the bio-based economy. Raw materials include more than biomass from agriculture, forestry and fishery or microbial production, with the importance of organic residues and waste materials as valuable resources increasingly being recognised. The goal and challenge is to create material cycles that are as closed as possible.

The bioeconomy is characterised by being based on renewable resources: Biological resources, i.e. living organisms such as plants, animals and microorganisms, whose metabolism produces a wide variety of organic substances as they grow and thrive. All these renewable resources can be subsumed under the concept of biomass. In the bioeconomy, biomass is used in a variety of ways – primarily as food and animal feed, but increasingly also as a source of materials or energy for industry. Renewable raw materials from sustainable production help save fossil resources and reduce greenhouse gas emissions, while creating jobs and adding value in rural areas.

Biomass from fields and meadows

Plants are the key biomass producers on earth: Through photosynthesis, they use sunlight to convert CO_2 from the air into oxygen and organic compounds. Biomass contains a complex mixture of carbohydrates, lipids (such as fats and oils) and proteins. Most of the primary biomass produced on land is based on green plants. Plants are at the start of the agricultural value chain, which makes them vital for the bioeconomy. Germany produces a wide array of plants, ranging from arable and crop farming to silviculture, horticulture and orchards to the cultivation of speciality crops such as wine or hops. Almost half of Germany's surface area is managed and maintained by farmers. Crops are mainly grown for food or animal feed. The predominant agricultural products for human consumption are grain for bread, potatoes, sugar beets, vegetable oils, fruits and vegetables, as well as animal products.

Today, grain is the most important plant product in German agriculture and is cultivated on more than a third of the agricultural land; most of it ends up as animal feed. The most common grain grown in Germany is wheat, followed by barley, which is mostly used for cattle feed, but also as malting barley for brewing beer. With bread being a staple food in Germany, rye is also quite important, along with starch-rich potatoes and corn. Sugar beet is the most important supplier of sucrose, or caster sugar. Germany's food industry uses large amounts of rapeseed oil, while wheat or rapeseed are also important sources of protein. Recently, legumes such as lupins, field beans and peas have risen in popularity. There is research into improving the performance of these domestically grown protein plants in order to reduce dependence on international imports. The bioeconomy has come up with new approaches to making the cultivation and use of plants more resource-efficient and sustainable, while ensuring the best possible coexistence of conventional agriculture and organic farming.

Another goal is the creation of new opportunities for plants as renewable raw materials beyond the food, feed and nutrition industries. Cereals, rapeseed, sugar beet and other crops also play an important role in the generation of renewable energies *(see chapter Energy)* and as raw materials for the chemical industry *(see chapter Chemical industry)*.

While plants are key biomass producers on land, algae and other primary producers perform this task in the water. Algae – both in the ocean and in fresh water – produce large quantities of sugar molecules and oils that offer interesting options for industrial use. In Europe, the food industry uses algae as emulsifiers, thickeners and food supplements.

The production and use of biomass in Germany

According to the Pilot Report on the Monitoring of the German Bioeconomy, almost 185 million tonnes of biomass (dry weight) were produced in agriculture, forestry and fishery in Germany in 2015. Agriculture contributed 137 million tonnes, forestry 48 million tonnes. 60% of the grain crops produced was used as animal feed, 17% for food, 10% as materials and 8% for the production of energy. As far as sugar is concerned, 87% was used for food and 10% for energy production. Vegetable oils and fats were mainly used for energy (34%), as materials in industry (28%) and as food (25%).

Algae can be cultivated in open or closed systems on degraded and non-fertile land, which means that they are not in direct competition with food and animal feed. Compared to crop plants, algae produce a ten times higher volume of biomass; however, their cultivation in photobioreactors requires much sunlight. There is ongoing research into the use of microalgae for the production of dies, proteins and vitamins for the cosmetics and food industries in order to make better use of this resource in Germany *(see chapters Food industry; Consumer goods).*

Biomass from stable and pasture

Farm animals are an important basis for the bioeconomy. Germany is a top producer of animal products: No other European country produces more milk and more pork, and Germany is the second largest producer of beef, veal and poultry after France. There are almost 200 million farm animals in total, which in turn consume around 80 million tonnes of feed per year. Animal husbandry and agriculture are closely intertwined.

Fodder crops, from arable pasture and from grassland management, provide most of the basic feed for livestock, such as grass or corn silage. By-products from sugar factories, grain mills and dairies are also processed into animal feed. As Europe does not produce enough high-protein animal feed, most of the demand is met through imports. Meadows and pastures are important for providing cattle with fodder, which makes them an important pillar of the dairy industry. They also contribute to the protection of the environment on account of being highly biodiverse. In this context, the challenge for the bioeconomy is to reconcile animal breeding, animal husbandry, the cultivation and production of food with sustainability and environmental protection *(see chapter Agriculture and forestry).*

Research into organic farming

The Federal Scheme for Organic Farming and Other Forms of Sustainable Agriculture (BÖLN) aims to promote organic agriculture and food production and other forms of sustainable farming in Germany, and to create a foundation for balanced growth of supply and demand. The scheme is funded by the Federal Ministry of Food and Agriculture (BMEL) and coordinated by the BÖLN office at the Federal Office of Agriculture and Food (BLE) in Bonn. Around 1,300 research and development projects have already been implemented, and the budget is more than 20 million euros a year.

Wood: a sustainable raw material

Forests play an important role in the provision of renewable raw material resources in Germany. They are valuable ecosystems, carbon stores, recreation areas and a source of wood – an important raw material. With a timber stock of 3.7 billion cubic metres, or 336 cubic metres per hectare, Germany is one of the biggest wood producers in Europe.

Its favourable material properties and small ecological footprint have been leading to a steady rise in the acceptance, demand and use of wood as a renewable raw material, building material and energy source. Domestic consumption of wood raw materials has increased continuously over the past two decades and the share of timber construction rose above 20% for the first time in 2020 *(see chapter Construction).* Logs are not the only forestry product, though: Other wood raw materials include wood chips or scheitholz from forest residues. In addition, by-products from the timber industry such as wood chips, sawdust and bark are important raw materials for wood-based value creation and employment in Germany.

The Charter for Wood 2.0 initiated by the BMEL is considered a milestone and a political framework for action to achieve the goals laid down in the Federal Government’s Climate Action Plan 2050. The Charter is a dialogue process involving all areas of society and addresses the use of wood as a climate-friendly raw material. The process is supported by the Federal Government, the Federal States, industry and science. The motto of the Charter for Wood 2.0 is: Mitigating climate change – Creating value – Utilising resources efficiently. It pursues three goals: Mitigating climate change through sustainable forest management and wood use. Creating value by maintaining and improving the value creation and the competitiveness of the forestry & wood cluster. And conserving finite resources through the sustainable and efficient use of forests and wood. The Charter for Wood is a joint effort. The different players are called upon to implement their own activities in the spirit of the Charter's objectives *(charta-fuer-holz.de)*.

The BMEL's Renewable Resources Funding Programme supports research and development projects with the aim of securing wood supply in the long term, increasing the use of wood as a material or for energy production, and effectively implementing a circular economy and the efficient use of materials and resources. At the same time, there are numerous research projects for breeding indigenous tree species that are more resilient to climate change in order to preserve the forest ecosystem. New management concepts are being developed on the basis of economic, ecological and sociological analyses, and the limits of what forest management can achieve are explored. In addition, state-of-the-art technologies are employed to further improve the properties of wood as a raw material for industrial use. A special focus lies on the increased use of non-coniferous wood, which has potential both as a material in its own right and as a raw material for the production of bio-based chemicals *(see chapters Construction; Chemical industry)*.

Microorganisms and insects

Microorganisms such as bacteria, yeasts and moulds present another important biological resource. For thousands of years, these tiny helpers have been employed in the production of foods such as beer or cheese. Microorganisms also cause the degradation of organic substances in biogas and sewage treatment plants. In the chemical and pharmaceutical industries, microorganisms have become important "workhorses" *(see chapters Chemical industry; Pharmaceutical industry)*. The following are important microbial cell factories: the bacterium *Escherichia coli*, *Corynebacterium glutamicum*, which is used in amino acid production, and the mould *Aspergillus niger*, an important supplier of citric acid. Insects are an alternative source of animal protein. 1,500 to 2,000 species of insects are consumed across more than 100 countries around the world. Like other animal-based foods, insects are rich in protein. As an added benefit, they can be cultivated in large quantities in a resource-efficient way. In Europe, insect products are covered by the Novel Food Regulation.

Forest timber as a resource

Germany has more than 11 million hectares of forest, which is 32% of its surface area. Forests provide numerous ecosystem services as well as raw materials. If we include residual and recycled wood (cascade use), a total of 127 million cubic metres of wood raw material per year is used for construction, as a material or as an energy carrier. At the same time, the forest is a valuable habitat for flora and fauna, a drinking water reservoir, a carbon store and a place for recreation. The conservation and expansion of forests, sustainable, semi-natural forest management and the substitution of energy-intensive, high-carbon and environmentally damaging materials with wood can all contribute to reducing greenhouse gas emissions and protecting the climate. The effects of climate change, such as more frequent periods of drought and weather extremes, are damaging the forest ecosystem. Every year, the Federal Government's Forest Climate Fund provides around 30 million euros for research and development projects that focus on helping forests to adapt to climate change. As of 2022, more than 250 research and development projects will have been funded. At the initiative of the BMEL, the German Federal Government has made an additional 480 million euros available for forests in the Joint Task for the Improvement of Agricultural Structures and Coastal Protection (GAK) for the period from 2020 to 2023. Adding to this funding from the Federal States, this amounts to almost 800 million euros. The economic stimulus package launched by the German Federal Government in June 2020 provided an additional 700 million euros for forests and wood. This includes funding of the Bundeswaldprämie (forest premium) for particularly sustainable forestry in private and communal forests.

In 2021, mealworms were approved as a “novel food” in the EU. While insect food is still a niche product, the great potential of insect protein as an animal feed additive – for example in aquaculture – has been recognised. Insects could also be used to supply raw materials.

The challenges of a circular economy

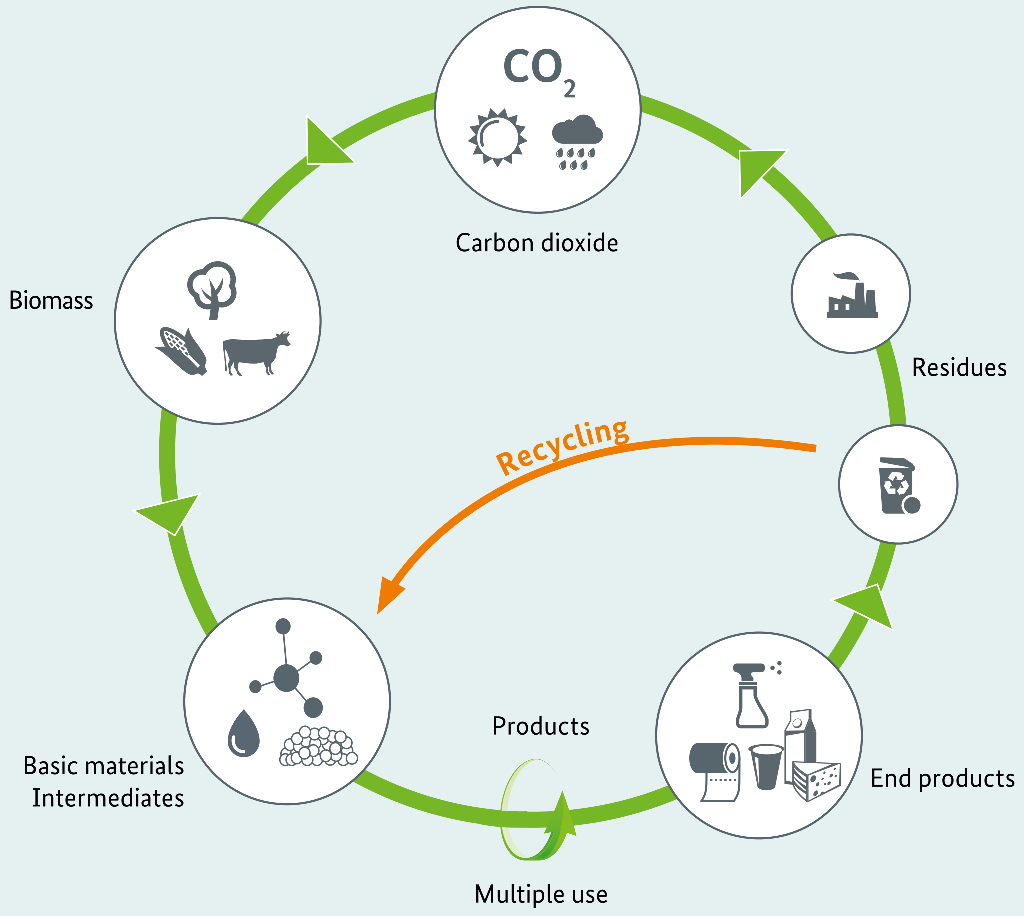
The bioeconomy does not just use the biomass produced, harvested and processed in agriculture and forestry. Its focus has shifted towards using the hitherto largely unused potential from harvest residues and residual materials such as straw, forest residues and liquid manure. In addition, there are traditional biological residual materials from industrial production and downstream processing, such as rapeseed press cake, biomass from algae residues, fermentation residues, whey and fruit peels, which are considered typical waste materials. To get an idea of the quantities of waste materials generated, the Deutsches Biomasseforschungszentrum (German Biomass Research Centre, DBFZ) has compiled a register of available resources and resources used. This project is part of the national Bioeconomy Monitoring Programme and covers biogenic residual materials, by-products and waste from five industries. Carbon dioxide has been receiving more attention, even though researchers have only recently started investigating the processing and further processing of the greenhouse gas. Biotechnology has made some progress in terms of the direct use of CO_2 and the use of synthesis gas from industrial processes as a carbon source. Microorganisms can convert carbonaceous gases from steel production or biogas plants into bio-based chemicals.

The bioeconomy is set to establish a closed material cycle and the efficient use of existing resources in a cascade use model. The main goal is the multiple use of biomass by first using the carbon bound in a bio-based product as a material – if possible multiple times – and then, once the potential has been fully exploited, releasing the carbon in the form of CO_2 by generating energy. Take wood as an example: Cellulose is turned into paper, used paper is recycled into paper, then into insulating material for buildings, and – once it is no longer needed for this purpose – it is incinerated to produce energy. Similar cascade uses are conceivable for straw. According to estimates, around 43 million tonnes of straw (fresh mass) are currently produced in Germany, mainly from cereal crops. Between 20% and 30% of the straw produced could be used as a material and for energy production, but this potential is not yet being fully exploited. As far as animal residues are concerned, existing material cycles are already closely interlinked. Nevertheless, there is still untapped potential in terms of higher-value applications and multiple material use.

Focus on renewable raw materials

The Federal Ministry of Food and Agriculture (BMEL) has initiated the Renewable Resources Funding Programme, which promotes the use of agricultural and forestry raw materials of plant or animal origin in industry. The programme covers material use and energy generation and focuses on domains such as construction and housing, biomaterials and wood, sustainable bioenergy sources as well as raw material crops and biogenic residues. At the time of publication, the Fachagentur Nachwachsende Rohstoffe (Agency for Renewable Resources, FNR) is coordinating almost 900 research and development projects with a total annual budget of approximately 90 million euros.

Carbon cycle in industrial processing



The German Federal Government's National Bioeconomy Strategy aims at mapping nature's carbon cycle in the bio-based industry of the future. This means that it is not simply a matter of replacing fossil resources with renewable raw materials. Actually, the potential of biomass should be exploited much more effectively, with the resulting material flows being put to use in a resource-efficient and sustainable manner for various industries. Many different sectors are already working on various promising approaches. In the process industry, biorefinery concepts are being tested *(see chapter Circular bioproduction)*. At the same time, biological resources must be considered in their entirety. After all, an ideal circular economy poses major challenges for all involved because the material and energetic use of biomass does not require the same quantity and quality of the raw materials as the food and feed sectors. In addition, parameters vary depending on whether biomass is used as a material or for energy generation, and depending on the use case.

The availability of land is an important aspect: Even though biomass is renewable in principle, the availability of cultivable surface is a limiting factor. This is why an intelligent approach to biomass use is needed. The bioeconomy provides a framework for describing resource efficiency and sustainability on the basis of high-tech tools and bio-based production processes. This is the only way to ensure that the competition between different use cases for renewable resources, and the coexistence of organic farming and conventional agriculture and forestry, can be successfully managed. At the same time, the bioeconomy offers Germany the opportunity to add more value by using biomass, and to enable a sustainable development of rural areas.

Circular bioproduction

Bio-based production processes can make an important contribution to a sustainable, climate-neutral economy. The aim is to conserve resources and produce and use biomass efficiently. The establishment of a bio-based circular economy is the central goal of the National Bioeconomy Strategy. Biotechnology has a key role to play here, while many other technologies can help to build new value chains.

Compared to other forms of raw materials, biomass is particularly suitable for sustainable circular use. The bioeconomy is modelled on these natural material cycles and creates innovative solutions for the more sustainable production and use of biomass.

The potential for biomass production, especially on land, is limited, so the efficient and careful use of biological resources along the entire value chain is essential. The aim is to create a circular economy that produces a minimum of waste and residues using sidestreams. Resource-efficient and innovative technologies and production processes are equally important when it comes to creating a bio-based economy.

Bio-based management can make a key contribution to reducing the consumption of fossil resources and CO_2 emissions, which makes industrial processes more environmentally friendly. This means that the bioeconomy can make an important contribution to a sustainable and climate-neutral economy.

Sustainable soil management

The primary production of biomass is the first step in a value chain within the bioeconomy, while the sustainable cultivation of the required plants relies on suitable soils. Around 46% of the total surface area of Germany is used for agriculture and 30% is covered by forest. With 27.2 million hectares of land, soil is the most important factor in agricultural and forestry production *(see Chap. Agriculture and forestry).*

Soil is a sensitive ecosystem, which performs ecosystem services – such as the storage of water or carbon, which have a direct impact on climate change. The potential ecosystem services have been identified by the first national Agricultural Soil Inventory, which involved soil samples being taken from more than 3,000 locations across Germany by the Thünen Institute of Climate-Smart Agriculture. The sample analysis showed that the top 1-m-layer of agricultural soil contains 2.5 billion tonnes of organic carbon, with two thirds of the carbon in the top 30 centimetres. Bog soil and other soils impacted by water in northern Germany and the Alpine foothills store a particularly large amount of carbon. The soil condition survey funded by the BMEL is set to be repeated every ten years in order to collect important data for sustainable soil management and climate action.

The formation of soil is a lengthy process, which means that soil cannot easily be renewed or replaced. It is therefore hardly surprising that science has a growing interest in how the performance of agricultural soil can be sustainably maintained and improved. Diverse crop rotation, the cultivation of catch crops, the addition of organic residual materials and organic fertilisation all contribute to the formation of humus and a balanced nutrient cycle. It is also important to have an active soil life with an abundance of animals, plants and microorganisms.

The BMBF specifically supports research activities on sustainable soil use through the programme Soil as a Sustainable Resource for the Bioeconomy – BonaRes, a long-term funding initiative. This initiative comprises ten research consortia working to deepen the scientific understanding of soil ecosystems and to improve the productivity – and other functions – of soils, as well as to develop new strategies for the sustainable use and management of soils.

Cells as biofactories

When it comes to the bio-based value chain, industrial biotechnology has an important role to play. It uses microorganisms, cells and enzymes as biological helpers, which have the task of transforming renewable raw materials into high-quality intermediate or end products.

As nitrogen fixers, legumes play an important role in sustainable soil management.

Microorganisms are adept at converting substances by fermentation, a process much used in industrial biotechnology. Fermentation is a metabolic process through which microorganisms convert biomass into other molecules, such as organic acids, amino acids, alcohols, biopolymers, therapeutic proteins or enzymes. Microbial enzymes can, in turn, be used as special tools to convert, degrade or refine bio-based products. Biocatalysts have become indispensable "production assistants" in the food, feed and consumer goods industries. Currently, only a few dozen production organisms are used in industrial production. Besides bacteria, yeasts and moulds, these include animal and plant cell cultures, which are converted into efficient cell factories to serve in biotechnological production processes. To ensure the optimal performance and reproduction of these sensitive cell factories, they are grown under the most suitable conditions possible. Bioreactors – or digestors – are the heart of every biotechnological production plant and rely on innovative bioprocessing technology *(see chapters Mechanical engineering; Pharmaceutical industry).*

Cascades and cycles

Produce, consume, dispose: Many of our typical value chains are actually one-way streets. One of the goals of the bioeconomy is to establish circular systems in which the volume of substances that leave the cycle is kept to an absolute minimum. To achieve this, natural raw and waste materials should not just be processed, but should be re-used and processed several times, or fully recycled.

Baker's yeast is an efficient cell factory used in industrial biotechnology.

In nature, biological resources form material cycles. The metabolism of living beings is part of the wider carbon or nitrogen cycle. This maintains a balance between the use and the creation of resources and ideally produces no waste or residue. Biomass is particularly suitable for sustainable use in cycles, both through material use and through composting. At the very end of the value chain, biomass can provide energy.

In principle, this does not release any more CO_2 than the amount that was taken from the atmosphere during the growth phase. Biological resources and bio-based products can offer a climate- and resource-friendly alternative to fossil-based raw materials and products. Bio-based cycles can be established wherever organic raw materials are already being used. In addition, bio-based alternatives to conventional materials and production processes can be developed. A key to the circular economy is the efficient use of resources along the entire value chain. Creating more from less: This applies to product design, production, consumption and the recovery of waste. The aim is to decouple economic growth from the consumption of resources. The central concept of cascade use is to utilise existing bio-based resources sustainably and as completely as possible, i.e. with all their components. The focus is increasingly shifting to the hitherto largely untapped potential of crop residues and residual materials such as straw, forest residues and liquid manure. In addition, there are traditional biological residual materials from industrial production and downstream processing, such as rapeseed press cake, algal biomass residues, fermentation residues, whey and fruit peel. They also include waste streams such as CO_2 or sewage sludge, though. Biotechnology has developed some promising options for the direct use of CO_2 and industrial synthesis gas as a carbon source. Microorganisms can convert carbonaceous gases from steel production or biogas plants into bio-based chemicals. This kind of microbial CO_2 recovery can close the carbon cycle through an industrial process, making it climate-neutral.

Microorganisms and enzymes can also help recover rare metals and phosphorus. Breaking down plastics into their basic building blocks could be the start of biotechnological plastic recycling *(see chapter Chemical industry).* Closed nutrient and reusable material cycles also play an essential role in innovative agricul-

The framework driving research and development of biorefineries

Biorefineries are technical installations in which plant biomass is broken down into its components and used as completely as possible – analogous to a petroleum refinery. Here are some pilot and demonstration plants at five locations across Germany where the biorefinery concept is being researched and refined:

Aachen: A pilot-scale biorefinery was set up at the Center for Next Generation Processes and Products (NGP²) of the Aachen Process Engineering Department at RWTH Aachen University. The modular facility was opened in 2017 and is funded by the Federal Government and the Federal State of North Rhine-Westphalia in order to research novel processes for converting green and woody biomass into platform chemicals and fuel components. RWTH is a cooperation partner of the Bioeconomy Science Center.

Leuna: The Fraunhofer Center for Chemical-Biotechnological Processes (CBP) is a leading research centre for biorefinery technology. The Federal Government and the Federal State of Saxony-Anhalt have invested 53 million euros in the development of the centre, which took up operation in 2012. The building complex in Germany's second largest chemical park offers space for several process plants *(see photo p.20)*. The focus is on the material use of vegetable oils, the separation and utilisation of lignocellulose from wood and the production of technical enzymes. Cooperation partners from research and industry can test the feasibility and economic efficiency of biotechnical and chemical processes for the use of renewable raw materials here.

Straubing: Clariant has built a demonstration plant for the biotechnological production of second-generation biofuels in Straubing. The 28 million euro project is funded by the BMBF and the Free State of Bavaria. Wheat straw and other crop residues are used to produce 1,000 tonnes of cellulosic ethanol annually. In Romania, Clariant completed a commercial plant based on the sunliquid process in the autumn of 2021. The plant converts up to 250,000 tonnes of straw into 50,000 tonnes of cellulosic ethanol every year *(see photo above)*.

Karlsruhe: The Karlsruhe Institute of Technology (KIT) is conducting research into the production of synthetic biofuels at its bioliq pilot plant, where straw and other lignocellulose-based biomass is processed into syngas. Customised fuels and basic chemical products are produced from residual biomass. The energy required for the process is covered by heat and electricity, which are a by-product of the process.

Hohenheim: At the agricultural experimental station "Unterer Lindenhof", the University of Hohenheim is testing the concept of a biorefinery farm in collaboration with KIT. The pilot-scale lignocellulose biorefinery will be using miscanthus grass as plant raw material to produce hydroxymethylfurfural (HMF), a basic chemical which is used for the synthesis of plastics and fuels, amongst other things. Process residues can be converted into energy in a biogas plant, and ultimately used as a fertiliser.

tural systems such as indoor farms by cleverly combining modern cultivation technologies and making controlled use of organic waste and residual material flows *(see chapter Agriculture and forestry)*.

Biorefinery as a concept for the future

Biorefineries are the major industrial factories of the bioeconomy. Similarly to a petroleum refinery, they break down biomass into its individual chemical components and utilise them as efficiently as possible. Biomass is a complex raw material, which not only makes it suitable as an energy carrier, but also as a precursor from which chemicals and other materials are extracted. Modern biorefineries are particularly consistent at implementing the principle of cascade use: Using a number of different technologies, biomass from a mixture of plant-based materials can be converted into a wide range of intermediate and end products. This enables a maximum of the biomass to be utilised, with material and energy use being combined. Each process step requires biotechnological know-how. Enzymes and microorganisms are used as tools for substance conversion. In most cases, physical-chemical methods are also necessary.

In order to use biomass sustainably and to avoid competition with food production, many modern biorefinery concepts are based on the utilisation of residues such as straw or wood waste. In Germany, the sustainability and efficiency of biorefineries as well as their scalability is being investigated at several large pilot and demonstration plants *(see box p. 23 and chapters Chemical industry; Energy)*. The challenges associated with the development of biorefineries were summarised by experts on behalf of the BMEL and BMBF in the 2012 Biorefineries Roadmap. According to this roadmap, biorefineries can contribute to the raw material shift, resource efficiency and climate action while producing completely new products as part of new value chains.

New value networks

Whenever the know-how from different technological domains – such as, for example, biology, technology and computer science – is combined, this creates great potential for the development of innovative processes and products in the bioeconomy. In addition to biotechnology, the following key technologies are also essential for the development of a bio-based

Innovative value chains for the bioeconomy

Various Federal Ministries promote the emergence of bioeconomy value chains. This leads to the creation of interfaces between research and application and connects the different players.

The **Federal Ministry of Education and Research (BMBF)** is funding four bioeconomy innovation areas with up to 20 million euros each. These cross-sector networks link industry and research institutions in order to speed up the implementation of the bioeconomy. Examples of innovation areas include bio-based textiles (BIOTEXFUTURE), the Frankfurt-Rhine-Main metropolitan region (BioBall), new food systems (NewFoodSystems) and the blue bioeconomy (BaMS).

The establishment of industry-led strategic alliances is also promoted by the Innovation Initiative Industrial Biotechnology. Research networks in the Bioeconomy Model Region in the Rhenish Mining District are exploring how the lignite mining industry can be converted to the bioeconomy.

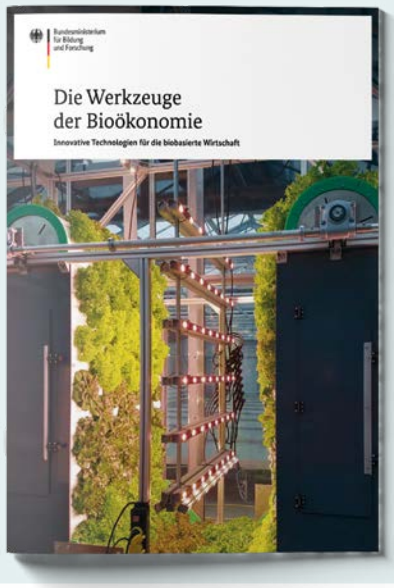
The **Federal Ministry of Food and Agriculture (BMEL)** supports programmes through the Innovation Promotion Programme and the Renewable Resources Funding Programme. This includes the ideas competition by Landcare Germany (DVL) for bioeconomy model farms in the low mountains and the project for bioeconomy model regions in central Germany and the Lusatian mining areas (MoreBio).

The **Federal Ministry for Economic Affairs and Climate Action (BMWK)** supports the development of an industrial bioeconomy, for example by promoting model regions and demonstration plants. The BMWK is advised by the dialogue platform Industrial Bioeconomy.

BMBF brochure: The tools of the bioeconomy

The brochure Die Werkzeuge der Bioökonomie (The tools of the bioeconomy), published by the Federal Ministry of Education and Research (BMBF) in March 2021, provides consolidated information on the most important tools and processes used as we move towards a sustainable, bio-based economy. 40 illustrated fact sheets depict the toolbox of the bioeconomy. The brochure explains biomolecules and cells, plant breeding and bioanalytics, industrial biotechnology and the agricultural production of the future. It also provides basic knowledge for anyone interested in the topic of the bioeconomy and is suitable for use in schools and universities.

biooekonomie.de/en/service/publications



circular economy: extraction, processing, production and recycling technologies, digital technologies for managing material flows and for exchanging data along the product life cycle.

Not only technologies are converging, but entire value chains. Sectors that previously hardly cooperated are now working together, creating new value networks, which produce innovative and sustainable products or services. The German Federal Government is creating a framework for such networks at the interface of science and industry in order to promote the translation of knowledge from research to application *(see box p. 24)*.

Publicly funded formats include innovation areas for the bioeconomy, strategic alliances, living labs and model regions. The government is also funding innovative SMEs through BMBF programmes such as SME-innovative: Bioeconomy.

Sectors and products

How can we achieve a bio-based and sustainable economy? What are the challenges? Which approaches are promising today? This chapter lists the key sectors already using bio-based production processes in alphabetical order and explains important research and innovation in this field. Many of these activities are publicly funded. The wide variety of bio-based products and processes shows that the bioeconomy is already an integral part of our lives.

Automotive industry

Examples from the bioeconomy: Natural fibre-reinforced body parts, bioplastic-based interior door panels and car seats, tyres made of natural rubber from dandelions

Construction

Examples from the bioeconomy: Timber construction, natural fibre-reinforced composites, insulation materials, bio raw plugs, bio-based concrete additives

Chemical industry

Examples from the bioeconomy: Bioplastics, bio-based platform chemicals

Energy

Examples from the bioeconomy: Wood pellet heating, biogas, biodiesel, bioethanol, synthetic fuels, algal paraffin, biohydrogen

Agriculture/Forestry

Examples from the bioeconomy: Precision agriculture, plant and animal breeding, short rotation coppice, aquaculture, indoor farming

Mechanical engineering

Examples from the bioeconomy: Bioreactors, bioprocess technology, biogas plants, agricultural technology and machinery, greenhouse technology, biolubricants

Food industry

Examples from the bioeconomy: Enzymes, flavours and amino acids, natural food additives, probiotics, food made from lupin protein

Pharmaceutical industry

Examples from the bioeconomy: Biopharmaceuticals, medicinal plants

Consumer goods

Examples from the bioeconomy: Bio-based surfactants, bioactive ingredients for cosmetics, enzyme-based cleaning additives

Textiles/Clothing

Examples from the bioeconomy: Natural raw materials for synthetic fibres, high-tech fibres made from spider silk protein, vegetable tannins, vegan leather substitute

Automotive industry

The car will continue to be an important component of mobility in the future. Alternative drive technologies are on the rise in response to climate targets and international competition. Manufacturers are turning to bioplastics and biocomposites to build ever lighter vehicles, conserve resources and implement a circular economy.

The transport sector causes about one fifth of Germany's greenhouse gas emissions, with more than 95% due to road traffic. As we move towards climate neutrality, the mobility sector is facing a fundamental transformation, with the car at its centre. According to the German Association of the Automotive Industry, there were more than 48 million passenger cars on German roads in 2020. Although domestic production has been declining since 2017, the production rate was still around 3.5 million vehicles in 2020. Sales at home and abroad totalled 378.2 billion euros in 2020, with around 809,000 people working in this sector. Internal expenditure on research and development was around 27 billion euros in 2018. In May 2021, the share of electric cars exceeded 20% of the total production for the first time.

Alternative drives of the future

One of the most important drivers of structural change in the automotive industry is the shift to alternative drive technologies. The industry's focus is clearly on electric motors powered either by batteries or hydrogen technology (fuel cells). The combustion engine will continue to play a role in the future, however – at least for some types of vehicles, such as commercial vehicles that require a long range or off-road vehicles, such as agricultural vehicles. Green fuels include biofuels and synthetic fuels *(see chapter Energy)*.

Petroleum is not just used in the form of petrol, diesel or lubricants. It is also the material from which many car parts are made: from paint to large interior parts, electronic components and displays. Around 10% of the German annual plastic production volume is used in the automotive industry. The main reason for the popularity of plastic is that it is light, easy to shape and has good thermal and sound insulation properties. Hybrid parts made of a combination of metal and plastic are also used. Some plastics are even robust enough to substitute metal.

Biomaterials for lightweight construction

The automotive industry is very much concerned with resource efficiency, lightweight construction and the circular economy. Carmakers are increasingly looking towards bio-based alternatives with a view to designing more resource-efficient vehicles and to making the production processes more sustainable. Plant fibres, bio-based plastics and natural fibre-reinforced composites for lightweight construction are used in the interior and body.

Actually, natural fibres have long been used in arm rests, luggage compartment floors and insulation. Fibres from coconut, beet or coffee grounds can be used as fillers. Natural fibre is also a popular material for reinforcing lightweight components such as the dashboard or the internal panelling of the car boot and doors, as well as in the car body. Materials made of flax, sisal or similar do not splinter easily, which is an advantage during processing and when accidents occur. Biocomposites contain plant fibres which are embedded in a petroleum- or bio-based plastic matrix.

According to the nova-Institute, around 150,000 tonnes of biocomposites were used by the European automotive sector in 2018. Volkswagen's subsidiary Seat, for instance, is running a pilot project using Oryzite, a biocomposite made from rice husk, polyurethane and polypropylene. The material is to be used in tailgates, in the load floor and in the roof lining.

Car manufacturers are also turning to bioplastics. These are either so-called drop-in solutions or novel and biodegradable bioplastics *(see chapter Chemical industry)*. Bio-based polyamide made from castor oil is used in high-performance components, polylactic acid (PLA) in interior door panels, soy-based foams in seat cushions and armrests.

One of the challenges when using bioplastics in automotive construction lies in their processability. This is why research and development often focus on how existing injection moulding processes can be adapted for the production of bio-based car parts. In addition, there is rising research interest in the recyclability of bioplastics.

The Institute for Bioplastics and Biocomposites (IfBB) of the Hochschule Hannover - University of Applied Sciences and Arts is working with all the major car manufacturers and companies along the value chain to pave the way for the development and industrial-scale production of bio-based materials. One example is a new project funded by the BMEL, which investigates the suitability of bioplastics for parts that are exposed to high temperatures and stress.

Self-repairing corn-based lacquer

Nanotechnology researchers have been working on self-repairing lacquers for more than a decade. In a project funded by the BMBF, researchers from the Leibniz Institute for New Materials in Saarbrücken and Saarland University developed a self-repairing vehicle lacquer using ring-shaped derivatives of corn starch, so-called cyclodextrins, which are threaded – like pearls – onto plastic molecules with long synthetic chains. When heated, the pearls become mobile and can compensate for gaps in the material, thus repairing superficial scratches. Paderborn University, in collaboration with PPG Hemmelrath Lackfabrik, has also been researching a bio-based, scratch-resistant and self-repairing lacquer with funding from the BMEL.

Biogenic fibres, resins and varnishes are used at the Fraunhofer Institute for Wood Research (WKI) to create lightweight components for the Bioconcept Car.

Racing test lab for bio-based materials

Bioconcept Car is an unusual alliance of a racing team, sports car manufacturers and material researchers. This project of the Reutlingen-based Four Motors racing team, which includes singer Smudo from the band Die Fantastischen Vier, has been around for more than 15 years. The goal is to design and test racing cars that are mostly built from biomaterials and run on biofuels.

Funded by the BMEL, the project has produced seven concept cars since 2003, which today regularly drive on the test track at the Nürburgring *(see photo p. 28).* Four Motors currently races Porsche cars. The Stuttgart-based car manufacturer has already been using natural fibre-reinforced plastics in a small series of the Cayman GT4 Clubsport since 2019. Biocomposites with a 30 to 70% share of renewable raw materials and bioplastic parts have been designed, manufactured and assembled as body and interior components for Bioconcept Cars. In addition to making the cars more eco-friendly, the flax-based natural fibres bring an added benefit: They are lighter than glass fibre and cheaper than carbon fibres. A research network which includes the Fraunhofer Institute for Wood Research (WKI) has developed biohybrid lightweight components for the Bioconcept Car. In a next step, the group comprising Fraunhofer researchers, Hobum Oleochemicals GmbH, Porsche Motorsport and Four Motors wants to develop a vehicle door with 85% of biogenic materials using a resin and lacquer composite.

Tyres made from natural rubber from dandelions

Rubber is in great demand and can be produced either petrochemically or on the basis of natural rubber. The latter is obtained from the milky sap of the rubber tree *(Hevea brasiliensis)*, which mainly grows in plantations in Southeast Asia. Natural rubber remains elastic even at low temperatures, which makes it the ideal material for winter tyres. However, forests have to be destroyed to make way for rubber plantations, and long transport routes make for high consumption of resources and CO_2 emissions.

Russian dandelion *(Taraxacum koksaghyz)* is a possible alternative source material which also grows in our moderate climate. The rubber from the milky sap of dandelion roots has the same molecular weight and elasticity as that from the rubber tree, and can be processed in exactly the same way. For many years, researchers from industry and science have been working on how to process dandelion rubber at industrial scale. Plant researchers from the University of Münster, the Fraunhofer IME and the tyre company Continental are leading the project.

Both the BMBF and the BMEL, as well as the European Union and the state of Mecklenburg-Antepomerania, have provided extensive funding for research and development into the industrial use of dandelion rubber. Their efforts cover the entire value chain: Modern precision breeding methods are intended to produce significantly higher-yielding and more robust plants. The alliance also wants to make the processing steps and the extraction of the plant raw materials more efficient and more sustainable.

For Continental, natural rubber from dandelions has become an important part of its sustainability strategy. The first Taraxagum test tyres for passenger cars were manufactured and tested in 2014, followed by the first dandelion HGV tyres two years later. In 2018, Continental opened its Taraxagum Lab, a research and development laboratory in Anklam / Mecklenburg-Antepomerania, Germany. This is where the first commercially available product was developed: a bicycle tyre, which has been on the market since 2019.

In 2020, the tyre was awarded the German Sustainability Award. In 2021, the team that had developed the dandelion rubber project was nominated for the Deutscher Zukunftspreis (German Future Prize), which is awarded by the German Federal President.

The Russian dandelion grows in our moderate climate and provides the rubber for the production of car and bicycle tyres.

Construction

Whether as a building material, for insulation or interior finishing: Renewable raw materials boast good material properties, improve the eco-balance and are often better for human health. However, even for conventional construction products such as concrete, bio-based, sustainable strategies are now available.

Construction is one of the most resource-intensive sectors in Germany. 90% of mineral raw materials are used for the production of building materials and products, and the building sector accounts for about 40% of total greenhouse gas emissions in Germany. Three quarters of these emissions are caused by the use and operation of buildings, while the rest is caused by the construction materials industry and construction activities themselves. This is shown by the environmental footprint of buildings determined by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR). With increased attention being paid to climate neutrality and sustainability, bio-based materials are increasingly coming into focus.

This means that the 325,000 businesses of the main construction industry and the finishing trade, which employed 2 million people in 2019, are of great importance for the bioeconomy in this country. At 277 billion euros, the sector generates about 6% of the total value added in Germany. According to the German Construction Confederation (ZDB), the timber construction sector alone accounted for 71,561 employees in 11,864 companies in 2020 and had a total turnover of 8.3 billion euros.

Wood – a building material of growing popularity

Wood is the most important renewable building and construction material there is, either in the traditional form of sawn timber produced by sawmills, or in the form of wood-based materials. In the production of chipboard, for example, wood chips are glued together and pressed into boards. Wood boasts excellent structural properties: Not only is it flexible, light and easy to work with, but also load-bearing, pressure-resistant and – after processing – it is extremely resistant to bending. What's more, wood is good for the climate: As they grow, trees store CO_2 by absorbing carbon dioxide and locking the carbon into their wood biomass. As a rule, less fossil energy is required for the production and disposal of building materials made of wood than for materials based on finite, mineral raw materials.

Wood creates a good indoor climate thanks to its pleasant surface temperature and its ability to regulate humidity inside buildings. Wood can be used for designs for new buildings, but also for urban densification or adding storeys to existing buildings. Timber structures can be efficiently prefabricated with high accuracy, which reduces construction time.

Digital planning and manufacturing

According to the German Timber Construction Association (Holzbau Deutschland), the timber construction rate exceeded 20% for the first time in 2020. The number of employees in the field of timber construction increased by 28% in the space of ten years. The working group on timber construction in urban and rural areas under the umbrella of the Charter for Wood 2.0 – a programme initiated by the BMEL – brings together players from industry, science and administration in order to promote timber construction.

More and more architects are opting for wood as a load-bearing structure. The BMEL's national HolzbauPlus competition awards prizes for outstanding timber construction projects *(see box on p. 33)*. One particularly impressive example of a modern, high-tech wooden building is the German National Garden Show pavilion designed by the University of Stuttgart for the National Garden Show 2019: The pavilion's load-bearing structure was inspired by the plate skeleton of a sea urchin and is made exclusively of fibre composites. The lightweight construction was designed digitally and manufactured in a robot-assisted process. In 2020, the design received a HolzbauPlus award. The Technical University of Munich is heading a BMEL-funded digitalisation project for the adaptation of Building Information Modelling (BIM) to timber construction. BIM, a 3D structural engineering planning method, supports all the digital workflows within the planning and construction process.

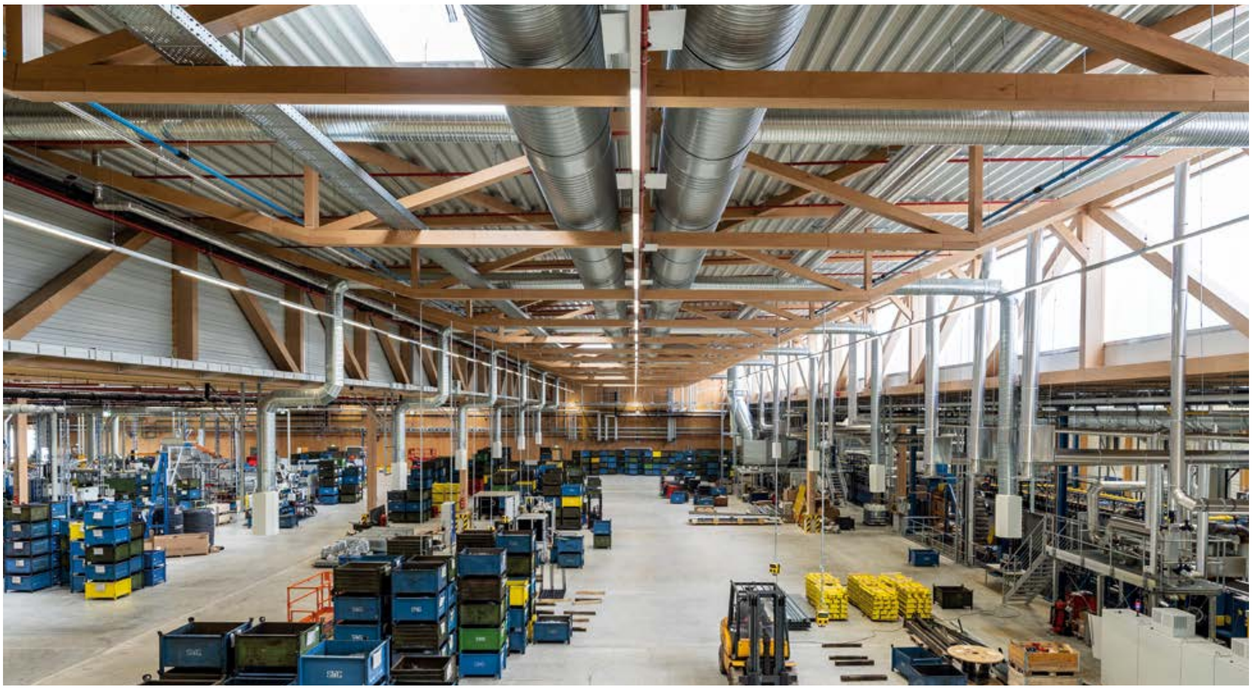
Unlocking the potential of non-coniferous wood

Traditionally, load-bearing components in timber construction have been made of coniferous wood such as spruce. But the attention of research and development in the construction industry is increasingly turning to non-coniferous wood. This is partly due to the fact that in our native forests, which are being converted to mixed forests in response to climate change, beech wood is already abundant and expected to become even more so. Currently, most of the non-coniferous wood is used for energy production, but modern bonding technologies are expanding its

National HolzbauPlus competition

The German Federal Government aims to increase the use of wood in construction in the long term. Since 2012, the BMEL has been organising the national HolzbauPlus competition, which will award construction projects using renewable materials for the sixth time in 2022/23. Private, commercial and public building owners are eligible to submit their construction and renovation projects. The relevant building components should be made of wood and the projects should have sustainable energy and heating concepts. One focus of this year's competition is on the design and implementation of renovation and conversion projects using wood.

holzbauplus-wettbewerb.info



The gigantic roof supporting structure at SWG's screw factory was constructed from laminated veneer lumber from beech called BauBuche.

potential: The Pollmeier sawmill, a specialist in beech wood processing, has developed a product called BauBuche, for example. This new type of material is produced by peeling wood off the beech trunk and then gluing it together in layers.

The resulting laminated veneer is a high-tech material that is suitable for structural timber design. Thanks to its great density, the load-bearing characteristics of laminated veneer lumber are close to those of steel. The SWG screw factory in Waldenburg is a case in point: At a size of 97 by 114 metres, the factory's roof truss is the word's largest roof made of BauBuche. The Thünen Institute for Wood Research analyses the structural properties of construction beech.

The German Federal Government and Federal State governments are supporting several innovative programmes for the application of non-coniferous woods such as beech and oak for the construction and other sectors. One such initiative is the Technikum Laubholz (Hardwood Technical Centre) in Baden-Württemberg. The BMEL also supports research initiatives to increase the material use of non-coniferous wood, such as the Charter for Wood 2.0.

Making concrete mixing more sustainable

Building with wood is not the only way to reduce CO_2 emissions in the building materials industry. The steel and cement industries have great potential to reduce the vast amounts of CO_2 they emit. As shown by the Fraunhofer Institute for Wood Research (WKI) in Braunschweig, there are ways of replacing steel in concrete with a fabric made from flax fibres. Flax fibre-reinforced concrete only requires half the thickness of steel-reinforced concrete in a bridge. There are a number of research projects that aim at improving the CO_2 footprint of concrete by employing bio-based raw materials, raising recycling rates and other approaches. Researchers in Berlin, for example, have developed a bio-concrete based on cassava peel ash *(see box p. 35)*.

A team at Hochschule München University of Applied Sciences is experimenting with adding bacteria to the concrete mix. If cracks appear and moisture penetrates, the microorganisms form limestone and repair the crack, which could extend the life of a building. Last but not least, wood and concrete can be combined to form hybrid materials. A BMEL-funded research initiative uses an innovative wet-on-wet adhesive bonding technology in which fresh concrete is poured onto a still-wet adhesive layer on a wooden support. Wood-concrete composite (WCC) floors bonded using this technique have a higher load-bearing capacity than conventional WCC floors, saving two thirds of the concrete and four fifths of the reinforcing steel compared with conventional construction methods. This reduces CO_2 emissions to one third.

Mushrooms as builders

Researchers at TU Berlin are working with fungi that can transform renewable raw materials into innovative building materials. Basidiomycota mushrooms, which may be edible varieties such as oyster mushrooms or inedible polypores such as tinder fungus, are best suited for the production of composites. The fungal mycelia convert plant residues into a stable and very light composite material. The big advantage of this material is that it can be easily composted. Experts in sustainable building at the Karlsruhe Institute of Technology (KIT) are researching "cultivated" building materials from fungal mycelia and how to combine them with digital manufacturing techniques.

Bio-based interior finishing

In this age of energy-efficient construction and renovation, natural insulation materials are becoming increasingly important. Their production is less energy-intensive and they have a positive effect on the indoor climate. These materials absorb large amounts of moisture and are often better for allergy sufferers. In 2019, the market share of insulation materials made from renewable raw materials was approximately 9%. With 58%, wood fibre insulation materials account for the largest share within this segment. Cellulose from shredded waste paper is also used as a raw material and makes up 32% of bio-based insulation materials, while hemp, flax, meadow grass, straw and sheep's wool account for smaller shares. As a research project funded by the BMBF has shown, agricultural residues can also be used as a basis for insulation material. The project team developed insulation materials for filling and blowing from corncobs. Corncobs are the central core of an ear of corn that is left over once grain maize has been harvested. In 2018, natural paints had a market share of 5%. Unlike conventional chemical products, natural paints are made from natural mineral or plant sources and require far smaller amounts of solvents. The most frequently used natural paint products are wall paints, wood stains, natural resin varnishes, oils and waxes. Floor coverings made from renewable raw materials provide the basis for wooden floors such as parquet, planks and laminate, as well as for cork and sisal floors. Linoleum consists of linseed oil, cork and wood flour, lime flour and pigments as well as jute fabric as a backing.

As we move towards a circular economy, recycling is becoming an important topic for the construction industry. ReMatBuilt, a German-Chinese research project funded by the BMBF, aims to improve resource efficiency in construction by recycling agricultural and forestry waste as well as construction and demolition waste. The goal of the project is to develop environmentally friendly hybrid building products, such as insulation panels made from rice or wheat straw.

Green concrete from cassava peel ash for Africa

Cement is the major component of concrete, and its production releases large amounts of CO_2. Together with partners from Africa, a team at the Federal Institute for Materials Research and Testing (BAM) in Berlin is developing a bio-based alternative to cement clinker from the peel of the cassava root (manioc), which is produced in huge quantities and disposed as waste in Africa. The ash produced by burning the peel is very suitable as an alternative to cement. The BAM now has bio-concrete cooperation projects with many African countries, including Nigeria and South Africa (vases 1 and 3 on the photo are examples). In 2018, the team was awarded the German-African Innovation Incentive Award by the BMBF.

Chemical industry

While the chemical industry is still predominantly based on petroleum, a fossil raw material, it is increasingly tapping into biomass, a complex and versatile raw material. More and more companies are turning to green chemical production based on renewable raw materials and biotechnical processes.

With around 2,000 companies, the chemical industry is one of the most important sectors of the German economy. At the beginning of 2021, the number of people working in the chemical industry was more than 464,400. Major international corporations such as BASF and Evonik have their headquarters in Germany. These key players generate the bulk of the chemical sector's annual turnover (2020: 190.6 billion euros). The chemical industry produces and sells a staggering 30,000 or more different products. Key clients include the plastics processing, the automotive, the packaging and the construction industries. Currently, petroleum and natural gas are by far the most important raw materials used by the chemical industry. In 2019, the consumption of fossil resources by the German chemical industry was around 17 million tonnes, from which basic chemical building blocks were obtained. These formed the basis of more complex compounds such as plastics, adhesives, varnishes and paints. Biomass is a versatile mixture of carbohydrates, fats, oils and proteins, which makes it suitable as a raw material for the production of chemicals. In 2019, the chemical industry processed 2.6 million tonnes of renewable raw materials *(see chart p.38)*. Most renewable raw materials used in the chemical industry today are vegetable oils obtained from palm fruits, rapeseed and soya, as well as animal fats. The oils and fats are then processed using chemical synthesis steps to generate bio-based surfactants, which are used in cleaning products, detergents and in cosmetic products *(see chapter Consumer goods)*.

Biotechnical processes also use renewable raw materials. After having been optimised for industrial production, microorganisms use sugar from beet, sugar cane, wood, straw and plant residues to power their cell growth and metabolism. This process is known as fermentation, and the microorganisms produce basic building blocks that can be used for more advanced chemical synthesis or even high-quality end products. Biomass can be the basic material for the production of organic acids, amino acids, alcohols, peptides, therapeutic proteins, enzymes and other biopolymers.

Compared with chemical synthesis, biotechnological production is often the more sustainable strategy because, unlike petroleum-based processes, microbial processes usually require an aqueous solution, and take place at room temperature and under normal pressure. What's more, microbial processes can produce substances which are difficult to produce using traditional methods. Examples include complex and large protein molecules such as enzymes, hormones or antibodies. This is the core business of industrial biotechnology. According to the sector association Bio Deutschland, out of 710 biotechnology companies in Germany, 10% said they were working in this area in 2020.

Growing interest in bioplastics

After fine and speciality chemicals, plastics are the second most important product segment for the chemical industry. Plastics are polymers produced from monomers, basic chemical building blocks, that are linked to form macromolecules during synthesis. Increasingly, manufacturers are turning to bio-based alternatives. Currently, about 1% of the plastics produced globally are based on renewable raw materials. According to figures by the European Bioplastics association and nova-Institute, the total volume was around 2.1 million tonnes in 2020.

There are two different types of bioplastics: Firstly, there are biodegradable plastics – but these are not necessarily made from renewable raw materials; some petroleum-based plastics are biodegradable. Bio-based plastics, however, consist of synthetic building blocks derived from biomass. We have to bear in mind that not all bio-based plastics are also biodegradable, though.

Bio-based plastics are mainly used in packaging and bottles, as well as in technical applications such as automotive construction or in the catering and agricultural sectors. Starch and cellulose in particular are important precursors for the production of bioplastics. While the first bioplastics were made from starchy fruits such as corn or potatoes, today, research is focusing on renewable resources that do not compete with food production, such as chitin, chitosan from crustaceans and insects, as well as lignin from woody biomass. These substances are waste products from other industries that have not yet been put to use much. Residues from agriculture and waste streams from the food industry include casein from non-marketable milk, animal fats from slaughterhouse waste and proteins from rapeseed processing.

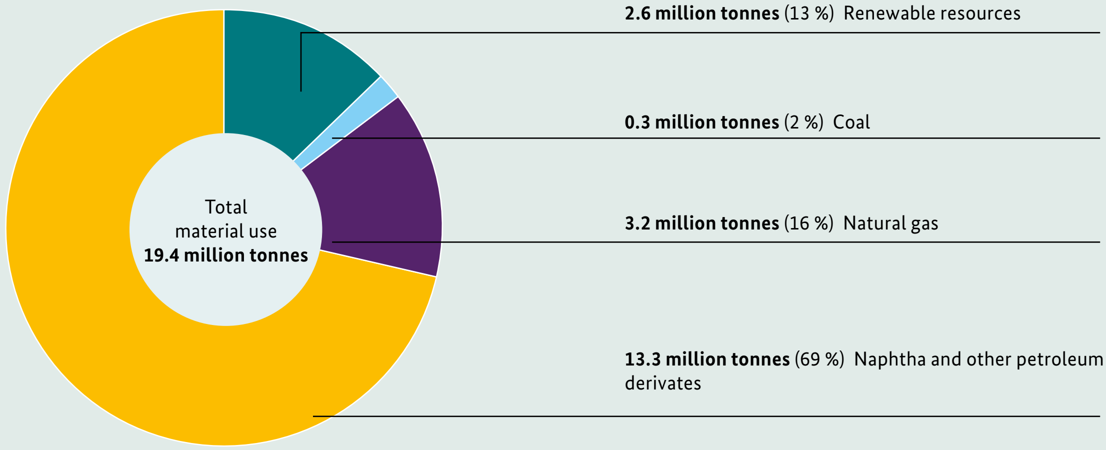
Drop-in solutions dominate

The world market for bio-based plastics is currently dominated by drop-in solutions. This means that

Is the switch to bio-based processes worth it?

How much sense does it make for a company to switch to bio-based chemical production? The EvaChem research initiative developed a system for finding the ideal production process for bio-based chemicals based on multiple criteria. The system can also be used to assess when a move away from fossil raw materials makes financial sense. Innovation-driven companies should be able to use the system to answer questions about the best possible combination of raw material, synthesis route and target molecule, for example. The aim of the new solution is to provide a reliable scientific basis and a manageable tool for small and medium-sized enterprises. The system was developed by the nova-Institute, Dechema and Leuphania Lüneburg, and was funded by the BMEL.

Raw material base of the German organic chemical industry (in 2019)



Source: VCI

bio-based basic chemicals, which have almost the same structure as the petroleum-based version, are integrated into the chemical synthesis. However, the resulting plastics, such as bio-polyethylene terephthalate (PET) or bio-polyethylene (PE), are not biodegradable. Evonik, a specialty chemicals company, sells PA610, PA1010 and PA1012 polyamides, which are completely or partly produced from castor oil, and which are used in a wide range of applications from the automotive to the textile industry. Covestro, a polymer manufacturer, has managed to produce aniline, an important precursor for many plastics, from plant-based raw materials. A project funded by the BMEL paved the way for bringing the process to industrial scale. In a biotechnological process, microorganisms use chemical catalysis to convert sugar from corn, straw or wood to an intermediate product and then to aniline. Covestro then uses aniline for the production of polyurethane foam for mattresses, insulation materials and car interiors. Plastics additives have also been receiving increasing attention from manufacturing companies. In a project funded by the BMBF, BASF is working with academic research partners from Hamburg and Bielefeld to develop bio-based plasticisers for the sustainable production of PVC. To make the process even more environmentally friendly, special enzymes are used to reduce the energy consumption and prevent the formation of harmful or environmentally damaging by-products.

Bio-based platform chemicals

In addition to drop-in solutions, novel bio-based plastics are on the rise, such as polylactic acid (polylactide, PLA). This bioplastic is obtained from linking lactic acid molecules, a platform chemical produced by microbes. PLA is both bio-based and biodegradable, and is mainly used in films and packaging. A German-Chinese research cooperation funded by the BMBF has established rice bran as a precursor for PLA. The use of this residual material (residual materials from starch or sugar factories are also conceivable) is set to be a decisive factor in making this plastic competitive. Through its ThyssenKrupp Uhde business unit, the ThyssenKrupp Group is currently building its second large-scale PLA production plant in China. The new plant is expected to produce 30,000 tonnes per year.

Biotechnological plastic recycling

Even though the fact that bio-based plastics are made from renewable raw material is positive, their recyclability and disposal remain major challenges. Material recycling of bio-based plastics is technically possible, but due to very small quantities of this material being on the market, recycling it is currently not economically viable. As a result, bio-based plastics are being incinerated. The carbon they are made of comes from biomass – not fossil resources –, so the process does not produce any additional CO_2, but does require renewable heat and electricity. While German law does not allow the industrial composting of biodegradable plastics, products labelled as “home compostable” may be put on the garden compost.

To establish a recycling system, adjustments in waste management are necessary. Experts emphasise the importance of multiple use, meaning that bio-based plastics should be reused as often as possible before being recycled and finally incinerated. In view of massive plastic waste pollution and microplastics in the soil and groundwater, the creation of plastic cycles remains the major challenge for the industry. In addition to mechanical and chemical recycling, there are now promising approaches using plastic-degrading enzymes for biotechnological recycling.

In 2016 in Japan, a bacterium was first discovered that grows on PET and also feeds on it. Researchers found out that the microbial enzyme PETase, among others, is responsible for the degradation of PET. The enzyme breaks down the plastic into smaller building blocks, while other enzymes split the plastic into its basic components. This ground-breaking discovery gave rise to numerous international and national research projects, such as the research consortium MIX-UP with the involvement of several German partners, which is funded by the EU and coordinated by RWTH Aachen University. The consortium develops processes using molecular-biologically optimised enzymes that efficiently break down PET plastic into its individual building blocks. Microorganisms will then use these components to produce higher-value chemical compounds in a value-added upcycling process.

Chemicals from biorefineries

Biorefineries are the industrial factories of the bioeconomy. Similarly to a petroleum refinery, they break down biomass into its individual chemical components and utilise them as efficiently as possible *(see chapter Circular bioproduction)*. As a rule, material

At the Fraunhofer Centre for Chemical-Biotechnological Processes CBP in Leuna, sustainable biorefinery processes are developed.

recycling and energy recovery are coupled with each other to create a wide range of new materials or bio-based chemicals. Different biorefinery concepts are being investigated and developed for commercial use across several German sites.

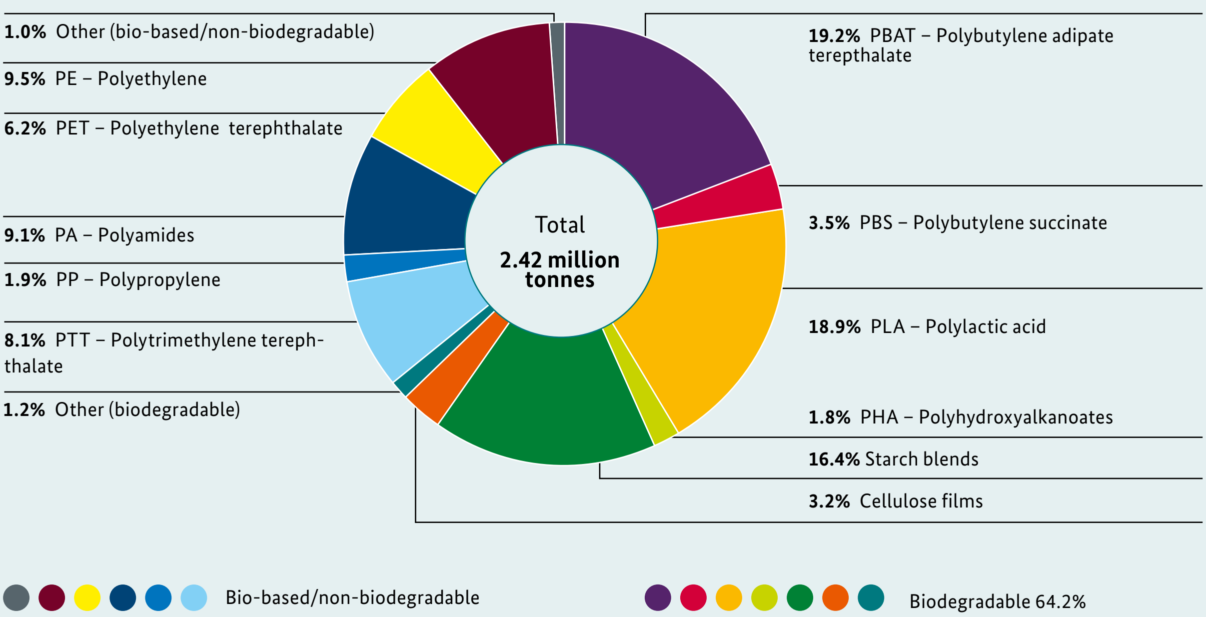
The Cluster BioEconomy in central Germany is one such example. At the Leuna chemical site, the Fraunhofer Centre for Chemical-Biotechnological Processes (CBP), which was set up with federal and state funding, is testing wood as a raw material in particular. CBP is attracting more and more companies, such as Global Bioenergies, a French company that is looking into new methods for the biotechnological production of so-called light olefins, such as isobutene, propylene and butadiene. The BMBF contributed around 5.7 million euros to the construction of a pilot plant which is designed to produce up to 100 tonnes of isobutene for the production of plastics, elastomers and fuels, for example.

The Finnish forestry and paper company UPM is building the world's first large-scale biorefinery for the chemical processing of beech wood in Leuna. The refinery, which costs 550 million euros, will break down waste from sawmills and forestry work into its components, sugar and lignin. UPM uses the sugar to extract ethylene glycol, which in turn is used to produce polyester and PET, among other things. Renewable fillers are made from the lignin, which could be interesting for the production of tyres.

Lubricants and adhesives

The German chemical industry has been producing approximately 2.5 million tonnes of lubricants annually for many years, and domestic sales in 2020 amounted to around 0.8 million tonnes. The market share of biolubricants is just over 4%. Currently, the most important applications for biolubricants are as hydraulic oils, turbine or engine oils and base oils. Most biolubricants are made from palm oil or palm kernel oil, followed by rapeseed oil, but sunflower oil is also increasingly used. Eight research associations funded by the BMEL are working on improving biolubricants for industrial applications in order to extend their scope of application. These include bio-cooling lubricants with corrosion protection, bio-hydraulic oils based on chitosan and bio-based thickeners for lubricating greases. Bio-based

Global production capacities of bioplastics in 2021 (by material type)



Source: European Bioplastics, nova-Institute

At its commercial production plant in Romania, the specialty chemicals group Clariant produces cellulosic ethanol from straw.

alternatives for adhesives are also becoming established. One advantage is that they are healthier than petroleum-based products, which may make them suitable for medical applications. Another plus is that they are mostly biodegradable. Last but not least, they often offer new functionalities. According to the German Adhesives Association, the market share of adhesives made from renewable raw materials was as much as 15% in 2017, and may well be higher for some classes of adhesives. The Leibniz Institute for Catalysis in Rostock and Henkel AG are collaborating in a BMEL-funded joint project to develop a new generation of adhesives by 2023. The resulting industrial and consumer adhesives are intended for assembly in the electronics and automotive sectors.

Electricity-driven chemical production

Electrochemical processes can be combined with chemical or biotechnological synthesis processes. It is possible to produce interesting chemical compounds from green electricity and renewable raw materials by electrosynthesis. The BMEL and BMBF's National Bioeconomy Strategy promotes the development of green chemical production processes. The BMEL has launched a call for funding for "Novel Paths to Electricity-based Conversion of Biogenic Raw Materials and Electrochemical Manufacturing of Biobased Products (Electrosynthesis)". The German Research Foundation also promotes electro-biotechnology by combining microbial and electrochemical material conversion. Fields of application range from wastewater treatment and soil remediation to the synthesis of chemicals and energy carriers.

Energy

Bioenergy from renewable resources remains an important element in the energy mix of the future. Agricultural farms can use biogas plants to produce electricity and heat. Even in a future electric mobility system, biofuels will still be needed for shipping and aviation.

With the energy transition, the German Federal Government intends to considerably increase the share of renewable sources of energy. To ensure that the energy supply continues to be reliable, secure and affordable, the Federal Government has set up the Energy and Climate Fund (EKF). The programme supports projects on renewable energies, national and international climate and environmental protection, electromobility and investments into boosting energy efficiency (including building refurbishment).

Bioenergy is a renewable energy, and one of the important building blocks in the energy mix of the future. Biomass, i.e. plants as well as plant and animal residues and waste, is considered a versatile source of bioenergy. It can be used to generate heat, electricity and fuels. On top of that it can be easily stored and bioenergy plants can be flexibly controlled. Biomass plants have the potential to compensate for fluctuations in the availability of other renewable energy sources, such as wind or solar power. According to the Federal Environment Agency, the largest share (55%) of renewable energies used in Germany in 2021 came from biomass. However, the available technologies are controversial because they do not yet meet all sustainability criteria. The first-generation biofuels such as biodiesel or bioethanol, for instance, are produced from oil- and sugar-containing plant crops that are also used for food production. This has created competition between “food, feed and fuel”. In Europe – and particularly in Germany – the use cases of bioenergy have been reassessed in recent years and the framework conditions have been modified. In the National Bioeconomy Strategy and elsewhere, the Federal

Government emphasises the priority of a secure global food supply over material and energy use. In future, biomass for energy generation should mainly come from organic residues and waste materials. Second-generation biofuels are produced from non-edible plant parts, i.e. residues and lignified plant parts such as straw or wood chips.

Wood as a heat source

Wood is an important fuel. In 2020, around 60 million cubic metres of wood were used for energy production in Germany (approximately 50% of the total wood raw material volume), 45.7% were burnt by private households. This means that a little over half of the wood used for energy is burned in biomass plants. 27% of the wood used for energy is solid forest wood (this is predominantly non-coniferous wood which is burned in private households). 24.7% of wood energy comes from sawmill residues and 22.5% from used wood, which is mainly incinerated in large combustion plants (> 1 MW).

The remainder is other types of wood such as landscape conservation wood. About 90% of renewable heat is generated from biomass. Modern, fully automatic pellet heating systems significantly reduce the emission of air pollutants such as particulate matter and carbon monoxide. The Agency for Renewable Resources (FNR) operates a website offering comprehensive information on heating with wood *(heizen.fnr.de)*.

Biogas: electricity and heat from fermentation

Biogas plants convert plants, animal excrement such as manure and other residual materials into biogas. Microorganisms ferment the biomass in airtight containers called digester. The result is a gas mixture which mainly consists of methane and CO_2. The biogas is then combusted in gas engines to produce electricity or heat. The residual material left after fermentation can be used as a fertiliser. Some plants convert biogas into biomethane by increasing the methane content and improving the quality of the gas until it is suitable for feeding into the natural gas grid.

According to the German Biogas Association, there were around 9,600 plants in Germany in 2020, generating more than 3,800 megawatts of electricity. There is still much room for improvement in process technology for biogas plants. Through the NextGenBiogas project, the BMEL is promoting the development of a new generation of flexible biogas plants *(see Mechanical engineering)*. The choice of energy crops is important, and the most common crop used today is corn silage. The Renewable Energy Sources Act (EEG) of 2021 aims to reduce the substrate share of maize and cereal grain to 40%. Attention is now shifting to perennial plants such as the sturdy miscanthus grass or the cup plant. The Berlin-based start-up SOLAGA takes a different approach: Microalgae film is used to produce biogas in small plants that can be installed in private households.

National Competition for Bioenergy Municipalities

Bioenergy municipalities and villages are pioneers of the energy transition, as the winners of the annual National Competition for Bioenergy Municipalities have proven time and again. The BMEL award honours villages and towns that meet their energy demand primarily from sustainable, renewable raw materials and biogenic residues. These places use biogas plants combined with wood, solar and wind energy to meet the demand flexibly and promote e-mobility. For the future, the goal is to store excess electricity and heat and to use it for domestic heating. These projects are initiated by the municipalities and implemented by local companies.

bioenergie-kommunen.de

In Clariant‘s demonstration biorefinery in Straubing, Bavaria, wheat straw is converted into cellulosic ethanol.

Biofuels in transition

As we strive for climate neutrality and switch to electricity and hydrogen power, there are some areas, such as heavy goods transport and shipping, where liquid fuels will remain important. Biodiesel is produced from vegetable oils or animal fats. In Europe, the largest share of biodiesel comes from rapeseed, which is suitable for the production of biodiesel because its contains up to 45% fat. Biodiesel from residual materials, such as used cooking oil and frying fat, is gaining in importance. According to the FNR, around 3 million tonnes of biodiesel from vegetable oil and used cooking oil were used in Germany in 2020.

Fermentation of manure

Animal husbandry produces considerable amounts of animal excrements such as liquid manure, slurry and dung. In the spirit of the circular economy, they are used as fertiliser on agricultural land. During storage and spreading, such manure produces considerable amounts of greenhouse gas emissions, in particular methane, which has a 25 times stronger effect on the climate than CO_2. The storage and spreading of manure adds an annual 250,000 tonnes to Germany’s total methane emissions of 1.9 million tonnes. This is why the German government’s Climate Action Programme 2030 includes the fermentation of farm manure in biogas plants as an important measure for the reduction of emissions caused by animal husbandry. To achieve this, the BMEL supports research and development projects as well as model and demonstration projects.

wirtschaftsduenger.fnr.de

Next-generation biofuels

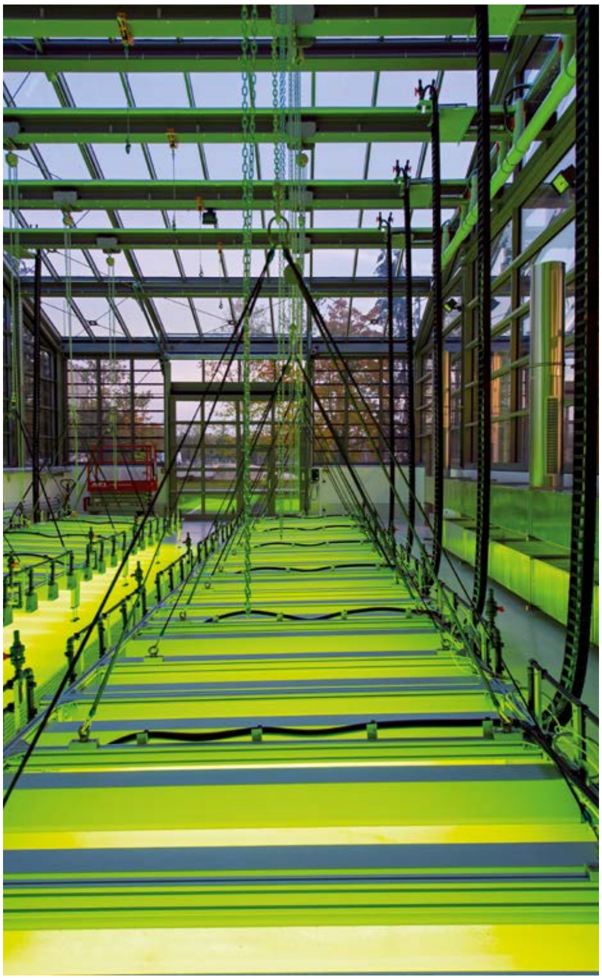
Biomass from agricultural residues such as cereal and corn straw, miscanthus and wood is in high demand for the production of biogas as well as other forms of bioenergy. However, lignocellulose, a substance contained in the cell walls, makes the efficient and complete use of plant residues, straw and wood difficult. There are different approaches to split up lignocellulose. Clariant, a chemical company, operates a demonstration biorefinery in Straubing in Bavaria, where straw is split up into its components and then converted to cellulosic ethanol through a biotechnological process. The bioethanol produced with the “sunliquid” process can then be added to petrol for combustion engines. At the end of 2021, the construction of a commercial biorefinery plant in Romania was completed with EU funding *(see chapters Circular bioproduction; Chemical industry).*

Usually, the soluble alcohol has to be separated from the water – a process which consumes much energy – before bioethanol can be produced. To overcome this challenge, recent research efforts have been looking into converting lignocellulose into a biofuel that does not dissolve in water easily. Alternatives include the long-chain alcohol butanol, which has different physical and chemical properties that make it insoluble in water, and which also offers higher fuel efficiency than ethanol. Processes for producing butanol from plants or plant residues are currently being developed. Global Bioenergies, a French company, has come up with a biotechnical process in which bacteria produce a gaseous hydrocarbon called isobutene. At its site in Leuna, Global Bioenergies produces isobutene, which can be converted into isooctane. The bio-based fuel is being tested by Audi to establish its suitability for standard use as part of a cooperation project.

Other sources of biofuel which are enjoying rising popularity include microalgae and cyanobacteria. These microorganisms perform photosynthesis, meaning they use the sun's energy to produce energy-rich sugar molecules from CO_2. In a subsequent step, microbial metabolisms can convert the sugars into lipids or oils, which in turn are processed into fuels. Experts refer to fuels which are obtained from photosynthetic organisms and CO_2 as a carbon source as third-generation biofuels. The AlgaeTec facility on the Bölkow Campus of the Technical University of Munich is a state-of-the-art algae research laboratory. Since 2016, research has been ongoing into the potential of algae of (mostly) marine origin to produce fatty oils, which are suitable for the production of aviation fuels and other industrial chemicals at extreme salt concentrations. The AlgaeTec facility was funded by the Federal State and by the Airbus Group. At the Algae Science Centre at Forschungszentrum Jülich, sustainable kerosene from algae oil is being investigated.

Synthetic biofuels

Biomass-to-Liquid (BtL) fuels are produced by thermochemical conversion. The complex molecules of the biomass are converted into a syngas (carbon monoxide and hydrogen) at high temperature. The syngas is then converted into liquid hydrocarbons – the desired fuel – using the Fischer-Tropsch synthesis, a principle which has been around for decades. Any elements contained in the biomass, such as nitrogen or sulphur, are separated. The synthetic fuel is free from foreign substances and has the same combustion properties as conventional diesel, for example. The fact that, potentially, the entire plant can be utilised, is a bonus and means that straw or woodchips are suitable for processing into BtL fuels. While the technology is not yet commercially used, BtL fuels are the subject of intensive research. At at pilot plant at the Karlsruhe Institute of Technology (KIT), the "bioliq" process, a production method for synthetic fuels, is being developed *(see photo p. 42).*



The AlgaeTec facility on the Bölkow Campus of the Technical University of Munich is a state-of-the-art algae research laboratory.

The bioeconomy in metropolitan regions

Agriculture, forestry and fishery traditionally provide the raw materials for the bioeconomy. All three of these industries are usually associated with rural areas. In urban areas, residual and waste materials are the major resource whose use has the double benefit of reducing the volume of waste and environmental pollution. The **BioBall – Bioeconomy in the Metropolitan Area** innovation area aims to leverage the potential of the bioeconomy within the FrankfurtRhineMain metropolitan region. The network has 31 partners, including 16 companies and 15 universities and research institutions, with the BMBF providing funding of up to 20 million euros until 2025. BioBall aims to promote the material use of biogenic residual and waste materials. This means that bio-based by-products and residual material streams from the private and municipal sectors are converted into raw materials for the food, chemical and pharmaceutical industries. One of the projects is looking into using CO_2 from industrial biogas plants as a renewable carbon source for chemical synthesis. Another project is investigating municipal pruning residues as a potential basis for green chemistry. Researchers are using these residues for fermentation to see whether they can produce electrode material for electro-biotechnology. Microbial fuel cells can help treat waste streams and wastewater as well as produce sustainable electricity.

biooekonomie-metropolregion.de

Sources of biohydrogen

Hydrogen is considered the energy carrier of the future because of its low-carbon production and use. Green hydrogen is currently mainly produced by water electrolysis, a process which uses large amounts of electricity from renewable sources. However, there are some bio-based methods to produce green hydrogen, such as the photosynthesis of green algae or bacteria. As part of this process, water molecules are split up into oxygen, protons (i.e. hydrogen ions) and electrons with the help of light energy and enzyme catalysis. Certain enzymes, known as hydrogenases, then help to produce hydrogen molecules. A research team from Kassel has managed to convert cyanobacteria into biological hydrogen factories using molecular tools. Under specific conditions, microorganisms can also convert biomass into hydrogen and CO_2 in biogas plants. This is referred to as dark fermentation. Both methods for the production of biohydrogen are being explored intensively.

Bio-based energy storage

Almost all common batteries contain metal compounds based on lithium, lead or vanadium, which are difficult to extract and to recycle, and often associated with environmental problems. The BMEL is currently funding the development of a plant-based alternative. The project is aimed at stationary redox flow batteries, which are able to store energy on an industrial scale. This requires electrolytes that are to be extracted from lignin, a wood component. Biogas plants can also be used as a flexible element of the electricity sector by serving as chemical energy carriers and storage. A project funded by the BMEL is looking into ways in which biogas plants can be combined with battery storage in order to open up new marketing channels.

From lignite to a bio-based economy: the Bioeconomy Model Region in the Rhenish Mining District

With coal being phased out, Germany's lignite regions are facing structural change. Thanks to its many industrial players, the Rhenish Mining District located between the cities of Düsseldorf, Cologne and Aachen has the resources to become a model region for sustainable industrial management with international appeal. The German government's Structural Development Act for coal-mining regions provides the funding for the Bioeconomy Model Region in the Rhenish Mining District. Biogenic resources and biological innovations are the foundation of new value chains and business models for the region that are now being tested and established.

In January 2022, three large research consortia were launched with funding from the BMBF to the tune of 72 million euros until 2026.

- **Innovation Cluster BioökonomieREVIER:** 14 innovation labs across three innovation clusters will enable the rapid translation of research ideas into commercial application: innovative agriculture, biotechnology & plastics technology and integrated biorefinery

  biooekonomierevier.de

- **Bio4MatPro:** Competence Center for the Biological Transformation of Materials Science and Production Engineering. This innovation network pools the expertise of companies and research partners to generate high-value products by bringing biological functionalities and bio-inspired principles into and onto materials. The respective production technologies are also being developed.

  bio4matpro.rwth-aachen.de

- **Understand. Connect. Support the Bioeconomy:** Accompanying research for the model region

Agriculture and forestry

Agriculture and forestry are important pillars of the bioeconomy. Plant biomass produced in meadows, fields and forests is one of the foundations of the bio-based economy. Modern cultivation technologies enable a more sustainable and resource-efficient production.

Agriculture and forestry are important industries. According to the BMEL, in 2020, Germany counted almost 263,000 agricultural enterprises and around 29,000 forestry enterprises. Agriculture and forestry are responsible for a large part of the value created in rural areas. Farmers and foresters manage and maintain more than three quarters of the land. Apart from their primary task of growing food and feed, they also produce bio-based raw materials for industry and biomass for the generation of renewable energy. These raw materials include wood, industrial and energy crops such as rapeseed, corn and miscanthus, as well as by-products such as liquid manure and straw. In digestors, agricultural biomass is converted into precursors for bio-based plastics and other sustainable chemicals *(see chapter Chemical industry)*. In biogas plants or combined heat and power plants, this is converted into heat, electricity or fuel *(see chapter Energy)*. Wood from forestry is a significant and versatile resource for the bioeconomy: It can be processed into sawn timber or plywood, wood-based materials or wood-plastic composites, pulp products such as paper or cardboard, pellets or briquettes and many other innovative products. The Forestry & Wood Cluster (excluding the publishing and printing industries) generates a turnover of approximately 131 billion euros through 98,524 companies with 732,140 employees.

The goal: sustainable agriculture

Around half of Germany's land is used for agriculture. According to the BMEL, out of the 16.6 million hectares of agricultural land, 70% is arable. A further 29%

is used as grassland and only 1% for permanent crops such as fruit or wine. More than half of the agricultural land in Germany is used for growing animal feed, and about a quarter of the land is used to grow plant crops for direct human consumption. The remaining area is used for the production of renewable resources for energy and industrial use.

Arable production systems are the cornerstone of food production. In the face of a growing global population and limited availability of arable land, climate change and the need to preserve biodiversity in natural habitats, arable farming must become more resource-efficient and sustainable. The 2035 Arable Farming Strategy identifies key fields of action for arable farming and for the contribution of the agricultural industry to protecting the environment, the climate and resources.

Bioeconomy research for agriculture pursues several goals: firstly, to reduce the required surface area and to boost the yield of crop plants by efforts such as modern plant breeding. Secondly, to reduce greenhouse gas emissions and other environmental impacts in agricultural production. One possible solution is to adapt farm management precisely to the location. Resources such as soil, water and nutrients must be used as efficiently and sustainably as possible. At the same time, species decline in the agricultural landscape must be halted and biodiversity must be strengthened by promoting ecosystem and structural diversity.

Modern plant breeding

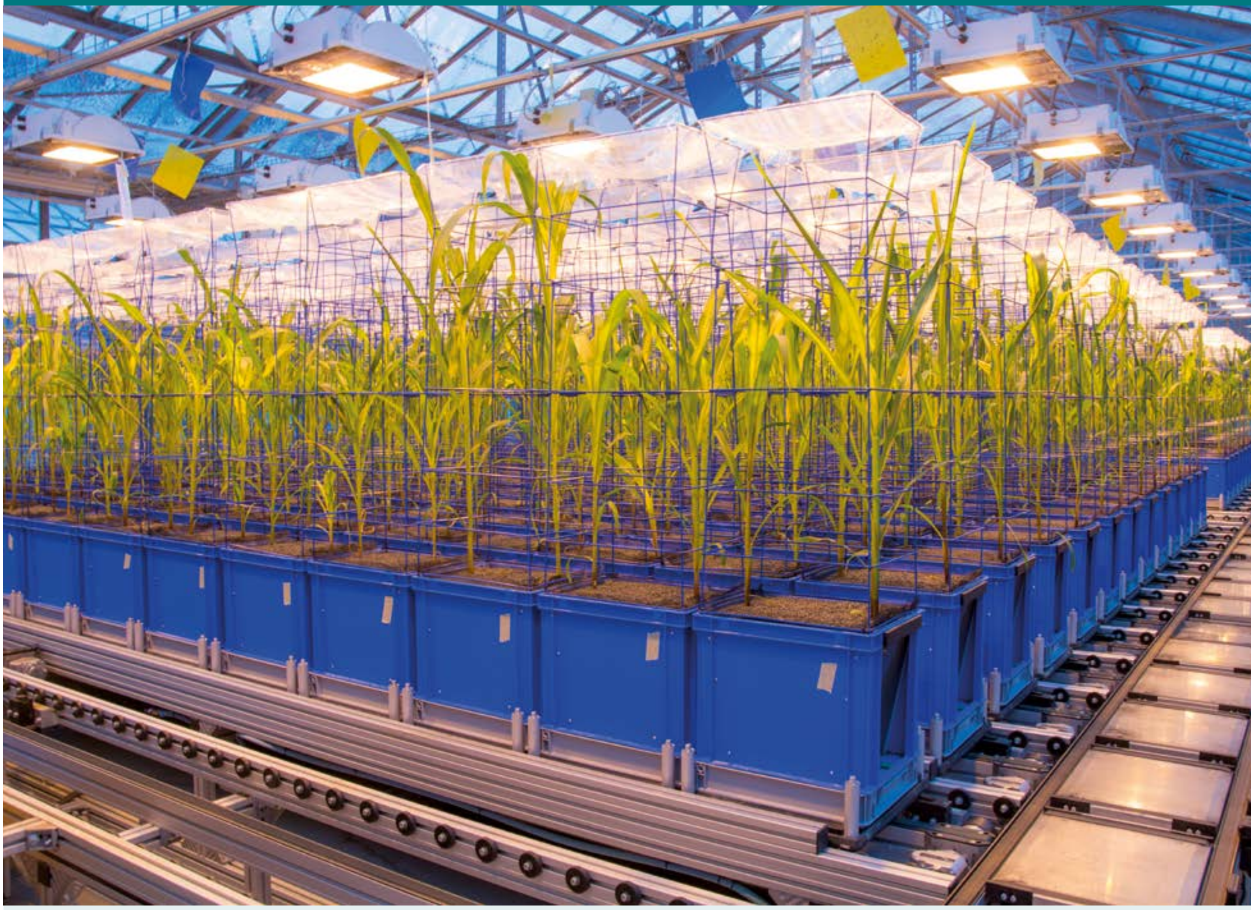
Modern plant breeding does not just have the single goal of increasing yields. It is also a matter of expanding the diversity of varieties and increasing the range of interesting plant ingredients. There is a strong demand for new varieties that are better able to cope with climate change, i.e. that are resistant to drought, excess salt or pest infestation, for example. Modern, knowledge-based plant breeding combines the latest findings from genetics and molecular biology with modern agricultural technology and sustainable soil management. New molecular biological breeding techniques are now complementing established breeding techniques. These include genome editing (such as CRISPR-Cas), which can be used to change the genetic material of crops in a targeted manner. Using other innovative breeding methods such as precision breeding based on genetic markers (smart breeding) or cell culture techniques, breeders can obtain high-yielding crop varieties that are more resistant to pests, diseases or weather extremes, and they can do so much faster and in a more targeted manner than ever.

Genome research provides a central knowledge base for modern plant breeding. German research teams are among the world leaders in this field. They carry out research into barley, the second most important grain crop in Germany. Despite its size and complexity, the barley genome has now been completely

How the BMEL supports innovation

Through its Innovation Promotion Programme, the Federal Ministry of Food and Agriculture (BMEL) supports research and development of technical and non-technical innovations in Germany. Funding covers projects on agricultural technology, plant breeding, plant protection, livestock breeding, animal husbandry and animal health, food safety and quality, nutrition, food production, aquaculture and fishery. The cultivation of renewable raw materials can also contribute to making the agricultural landscape more diverse. Through its Renewable Resources Funding Programme, the BMEL supports so-called landscape laboratories, where sustainable cultivation systems are developed.

Making crop plants fit for the future



Whether high-yielding grain crops, fungus-resistant sugar beet or faster-growing poplars: The development of improved crop plants requires innovative research and fast transfer. Research programmes for applied plant research funded by the BMBF have been integrated under the umbrella of **PLANT 2030**. One such programme is the **Plant Breeding Research for the Bioeconomy** funding initiative, which is part of a joint initiative with the BMEL. The main aim of BMBF funding is to increase knowledge to create a foundation for innovation in plant breeding research. BMEL funding on the other hand is geared towards application-oriented, pre-competitive projects. What they do have in common is that public research institutions and companies are cooperating to advance plant breeding and related areas of the bioeconomy. The projects on applied plant research draw on the knowledge gained by genome research in recent years, which are relevant for the entire agricultural sector. The funding goes to projects for applied, interdisciplinary research into functional biodiversity, precision breeding, resource efficiency and “green” bioinformatics for applied crop research. Epigenetics is the science of heritable changes in gene activity that are not based on changes to the DNA sequence. A research project funded by the BMBF programme **Epigenetics - Chances for Plant Research** is investigating how epigenetic mechanisms can be applied to plant breeding. The focus of the BMBF funding initiative **Plant roots and soil ecosystems - significance of the rhizosphere for the bioeconomy (Rhizo4Bio)** is on how plant roots and soil ecosystems interact. Research networks are investigating the interplay of roots, microorganisms and soil which determines the nutrient and water uptake of a plant and has an effect on drought resistance, amongst other things. We need approaches that can help plants adapt to the climatic conditions of the future – for example droughts – and make them more resilient.

pflanzenforschung.de

deciphered. An international consortium led by scientists from Gatersleben published the barley reference genome in 2017. This was the first complete and highly resolved genetic sequence. The experts identified around 5 billion base pairs and put them in the right order. Today, researchers are analysing the barley pangenome, i.e. the entirety of the genomes of the many different variants from around the world. This creates a valuable resource for global plant breeding.

In recent years, German researchers have also been instrumental in sequencing and analysing the vast genomes of rye and bread wheat. The BMBF supported the genome projects within the framework of Plant 2030 *(see box p. 50)*. Through the TERTIUS lighthouse project, the BMEL supports a consortium that intends to build on the genome data to breed high-yielding wheat varieties with a strong resistance to drought. Crop plants with deeper and more branched roots should be able to cope better with ever more frequent periods of drought during the spring and summer months.

Additional research approaches use state-of-the-art techniques to simulate various climate scenarios in the greenhouse in order to calculate their effects on growth and yield. This kind of work is being performed at the Helmholtz Centre for Environmental Research in Bad Lauchstädt, among other places. Another area of investigation is the connection between plant genes, the environment and the phenotype, which has an effect on the structure, function and efficient use of a plant's resources.

Phenotyping is used to search and measure plants for complex external traits or characteristics without harming or destroying them. The BMBF has funded the establishment of the Deutsches Pflanzen Pänotypisierungsnetzwerk (German Plant Phenotyping Network, DPPN), which has set up modern high-throughput facilities for screening plants in Jülich, Munich and Gatersleben.

Increasing soil fertility

Sustainable, bio-based management has always been at the core of organic farming. One of the principles of the organic farming cycle is that a farm grows its own animal feed without easily soluble mineral fertilisers and chemical crop protection. To keep the soil fertile,

Researchers at the IPK Gatersleben are among the world leaders in barley genetics and genome research.

organic farmers fertilise with manure or slurry, or they use legume crop rotation. While the total number of farms in Germany is declining, the number of organic farms is steadily growing. In 2020, there were around 35,400 organic farms in Germany, which is about 13.5% of all farms. A key challenge in organic farming is that the yields are lower than in conventional farming. Accordingly, there is great interest in new research findings on land use and soil fertility and other strategies to sustainably increase yields.

Wet bogs as a resource

Wet bogs are excellent carbon sinks because peat is a very dense organic mass. However, as soon as peat comes into contact with oxygen – for example, when it is drained – it releases vast amounts of CO_2. If we want to use this soil for agriculture anyway, we have to develop wet production processes. The term paludiculture refers to the agricultural use of wet bogs. The University of Greifswald has specialised in paludiculture research, looking at its potential for the bioeconomy while protecting bogs and the climate. Both the BMEL and the BMBF support the research activities at Greifswald. The paludiculture activities in Lower Saxony are bundled by the Kompetenzstelle (Competence Centre) Paludiculture (photo). The BMEL also supports projects on peat reduction and bog soil protection, as well as model and demonstration projects on peat substitution in hobby and cemetery horticulture. Activities include the development of a certification system for peat substitutes as well as information on the subject of peat reduction for both experts and consumers.

The potential of legumes for this purpose has not been exhausted by far. Thanks to root-nodule bacteria, legumes can fix nitrogen from the air, which fertilises the soil. What's more, legumes are also valuable sources of protein. As part of its protein crop strategy, the BMEL is funding projects that are intended to give a new boost to the cultivation and breeding of protein-rich lupins, soya, peas and field beans in Germany. This also includes varied crop rotation and mixed cultivation. One BMEL project investigates the mixed cultivation of corn and runner beans. This boosts soil fertility, has a potentially positive effect on biodiversity and reduces soil erosion.

In the BMBF-funded IMPAC3 project, researchers from the University of Göttingen investigated different systems of mixed cultivation, for example the joint cultivation of winter wheat and winter fava beans. The results of the field trial are promising: The joint cultivation increased the nitrogen supply of the wheat by 40%, and the yield by more than 30% compared to a monoculture, while the need for fertiliser was reduced.

The BMBF programme Soil as a Sustainable Resource for the Bioeconomy – BonaRes consists of ten soil research associations that are also working on new concepts and strategies for sustainable soil management *(see Circular bioproduction).* The objective is not just to boost soil fertility, but also to increase the carbon storage capacity of the soil (carbon sink). In addition to new crop rotations – such as the cultivation of catch crops like clover, charlock or phacelia, a bee crop plant, the BonaRes teams are investigating how the community of microorganisms in the soil, the microbiome, can be improved. The interactions of plant roots and their direct environment in the soil are the focus of another BMBF funding initiative *(see box p.50).*

Digitalised agriculture

The immense technological progress made in the last few decades has enabled farming to move towards sustainable and resource-efficient agricultural management. Digitalisation also has an important role to play in this: Much of the information on soil, land use and the climate is now publicly available in digital form. In addition, the amount of data from aerial

Smart and sustainable: the Agricultural Systems of the Future

We need new solutions in order to make agricultural production more sustainable, resource-efficient and adaptable. The BMBF funding initiative **Agricultural Systems of the Future** focuses on innovative concepts to achieve this. Eight large consortia are exploring agricultural production that is highly digitalised, automated and interconnected, and that cleverly combines modern farming technologies. To create sustainable agriculture and adhere to bioeconomic principles, we need smart and high-tech engineering, artificial intelligence (AI), digitalisation and resource-efficient, closed energy and material cycles. The consortia are also working on alternative production systems for both rural and urban areas with new, partially unconventional approaches such as the AI-supported Digital Agricultural Knowledge and Information System (DAKIS) for the sustainable cultivation of crops, or small-scale island farming concepts. New approaches to pasture farming are being researched (GreenGrass) as well as agricultural concepts without chemical synthetic plant protection (NOcsOS). The focus is also on the development of modular, highly controlled and closed cultivation and production systems and the development of unconventional production organisms, such as jellyfish, salt plants or crickets (e.g. CUBES Circle, Food4Future). The partners of the SUSKULT project are developing hydroponic food production within sewage treatment plants. Closing the nutrient cycles between urban and rural areas is the objective of the RUN project consortium, while the aim of the ONFIELD project is to create better working conditions for farmers using semi-autonomous tractors. In total, the BMBF is providing almost 43 million euros for the eight Agricultural Systems of the Future.

agrarsysteme-der-zukunft.de

photographs taken by drones or earth observation satellites is increasing. More and more tractors and other agricultural machinery are being equipped with sensors and measuring technology that can record the condition of the soil or the plants.

This enables agricultural machines to analyse the water and nutrient requirements of the crops. Powerful computer applications using artificial intelligence (AI) help to evaluate the huge amounts of data. Plants can be watered, fertilised or cleared of weeds as needed and with precise accuracy based on satellite and weather data. This not only increases efficiency and yield, but also reduces the input of excess nutrients into the environment and lowers the costs for fertilisers, pesticides and seeds.

The use of small, autonomous and GPS-controlled field or harvesting robots or drones could counteract the problem of soil compaction. Digitalisation is paving the way towards a precision agriculture that is resource-efficient and environmentally friendly. It also allows smaller-scale and even pinpoint farming of arable land. Digital assistants also support animal husbandry: Sensor and measurement technology monitors animal activity, needs-based feeding, milking and the animals' health. Digital technologies have great potential to make crop cultivation more sustainable and ensure animal welfare. The BMBF's funding programme for Agricultural Systems of the Future puts a focus on agriculture 4.0 with smart machine and system networks using AI and other IT applications *(see box on p. 53)*. To promote digitalisation in agriculture, the BMEL funds digital trial fields and has initiated the funding priority HortiCo4.0.

Digitalisation in forestry

In forestry, digitalisation has not yet made as much progress as it has in agriculture. While the large private and public forest owners and the timber industry have already digitalised some of their business processes – albeit mainly with individual solutions – small private forests and smaller companies are more reluctant and have much catching up to do. Digital networking along the entire forest and timber value chain is still a long way off. The German Federal Government's funding policy has been promoting solutions, though.

In an online survey published in 2022 by the German Forestry Council and the Timber Working Group on digitalisation in the German and Austrian forestry and timber industries, 94% of the 256 companies surveyed said they were interested in learning more about digitalisation. However, 65% of respondents are currently not actually prepared to implement digital projects in the Forestry & Wood Cluster.

According to the survey, the biggest obstacle to implementation is the lack of standardised business processes, in particular compatible data interfaces. Insufficient connectivity in the forest and a lack of broadband internet connections in rural areas present additional hurdles, along with concerns about data protection and IT security.

However, digitalisation in the Forestry & Wood Cluster offers indispensable options for more efficient wood production and processing. Numerous initiatives and projects have emerged nationwide to

Stacked logs in a mixed forest

Poplars are harvested on a short rotation plantation

advance the issue.

Through the Agency of Renewable Resources (FNR), the BMEL alone is currently funding 15 research networks covering more than 40 individual projects concerned with digitalisation along the forestry and wood value chain. The Smart Forestry research initiative, for example, is developing a cross-cluster process for intelligent and fully integrated timber harvesting. The value creation networks based on the Forest and Wood 4.0 principles connect all players and systems involved in timber harvesting via digital twins on the Internet of Things.

The Contura project combines research and practice in order to develop a digital recording system for the condition of forest roads. This system is based on an artificial neural network which stores information about the condition of a forest road whilst it is being driven on. Data collected in this way is used to create a digital twin of the road while a snapshot of the actual road is digitally stored. Once the condition of the forest road has been recorded and evaluated, the digital twin serves as a basis for planning road maintenance – a prerequisite for forest work and timber harvesting.

Adapting timber production to climate change

Forests provide a large part of renewable materials used in Germany: wood. Forest trees lock carbon from CO_2 into their biomass, which is a significant contribution to climate action. As with agriculture, the major challenge lies in securing a sustainable supply of raw materials and adapting to climate change. Particularly between 2018 and 2020, calamities caused by droughts and storms caused extensive damage in German forests, and the bark beetle has spread extensively.

In addition to converting forests into climate-resilient mixed forests with tree species that are suitable for the habitat, forest plant breeding can help secure the supply of high-quality reproductive material. Breeding trees is particularly complex and time consuming. This is why the Federal Government and the Federal States have joined forces to create a breeding strategy designed to make six tree species (Douglas fir, larch, sycamore maple, spruce, pine, oak) fit for the future.

In addition, in 2021, the Federal-Länder Working Group Forest Genetic Resources and Forest Seed Law (BLAG-FGR) published a national concept for identifying tree species relevant for adapting to climate change with a view to establishing comparative cultivation projects. The German Federal Government's aim is to strike a sustainable balance between the increasing – and sometimes competing – burdens on the forest and its sustainable performance. The BMEL's Charter for Wood 2.0 addresses this issue *(see chapter The resources of the bioeconomy).* In addition, the Forest Strategy 2050 builds on this guiding principle by formulating policies for sustainable forest development.

Combining agriculture and forestry

Short rotation coppice, in which fast-growing trees such as poplars ad willows are cultivated, can be a meaningful addition to agricultural operations. These permanent crops can be harvested after just a few years. The BMEL has funded various plant breeding projects for the development of tree species suitable for commercial cultivation in short rotation coppice. Agroforestry combines woody plants such as trees or shrubs with arable crops and animal husbandry on the same land. The various components are intended to create ecological and economic benefits. Agroforestry can also be a strategy to remove more CO_2 from the atmosphere and contribute to climate action. The BMEL and the BMBF are funding several research projects on agroforestry.

Closed production systems

In recent years, new technologies have produced a growing number of mature, closed production systems. Highly controlled production conditions allow fruit and vegetable cultivation as well as animal husbandry all year round. Indoor farms are space-saving production systems with largely closed material and energy flows and coupled cycles. Moving food production into enclosed, heated and artificially lit spaces enables large-scale agricultural production in any location or climate.

With funding from the BMBF, the Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB) has developed an emission-free aquaponics system that allows cichlids and tomatoes to thrive together. CUBES

Focus on the blue bioeconomy – the BaMS innovation space

The **BaMS innovation space – Bioeconomy on Marine Sites** conducts research in the field of the so-called blue bioeconomy, by developing an aquatic circular economy. The aquatic circular economy is based on all forms of blue biomass, including algae, fish, mussels and other aquatic organisms, which serve as raw materials for processing in biorefineries or biogas plants. Members of the BaMS innovation space produce food, cosmetics, animal feed and raw materials for agriculture. The aim is to efficiently utilise raw materials and residual materials and to introduce new production and processing methods that will close the cycles and contribute to a more sustainable use of biogenic resources from the sea and fresh water. The innovation space covers 28 companies and 17 research institutions from northern Germany. The joint research and development activities are designed to foster a more sustainable use of aquatic resources and to strengthen the blue circular economy. The focus is on the implementation of projects and the establishment of model sites which will drive the shift towards a bio-based, blue economy. The BMBF is funding the innovation space with up to 20 million euros.

blaue-biooekonomie.de

Salad from the assembly line: The automated, vertical plant cultivation system OrbiPlant at the Fraunhofer IME in Aachen.

Circle, an Agricultural Systems of the Future project, has developed a closed food production system consisting of connected, mutually communicating and standardised production units with largely closed energy and nutrient fluxes for the cultivation of fish, plants or insects. Other innovative concepts focus on integrating the cultivation of plants into urban areas, such as roofs or facades.

More and more stakeholders are turning to urban farming to meet the demand for regional products and to make immediate use of residual and waste materials or waste heat generated on site. SUSKULT, coordinated by the Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT), is one such project which converts sewage treatment plants into suppliers of nutrients for vegetable cultivation in hydroponic systems. This agricultural system of the future investigates the cultivation of lettuce, duckweed and sweet potatoes, amongst others. Indoor farming also plays an important role in the Innovation Area “NewFoodSystems” *(see chapter Food Industry).*

Mechanical engineering

Germany is a global leader in mechanical engineering. Modern machinery, devices and processes can help make production sustainable and efficient in any industrial or economic sector. This is why innovation in mechanical engineering is an important driver of the bioeconomy.

Mechanical and process plant engineering has always been one of the mainstays of the German economy. In a bio-based economy, technical systems, machines and process technology are essential for resource-efficient and sustainable management. The particular engineering challenge lies in having to reconciliate technical and biological requirements. Depending on the specification, biological materials require dedicated machines, plants or processes. Digitalisation and automation – such as robotic solutions – drive innovation in mechanical engineering and combine mechanical engineering and machines in smart networks.

Bioprocess technology: optimal working conditions for cells

Biotechnological production processes rely on living cells to make chemicals, medicines, food additives and cosmetic ingredients. Conditions have to be very particular in order to ensure the optimal performance and reproduction of these sensitive cell factories. Bioreactors – or digestors – are the heart of every biotechnological production plant. Developing these plants, operating them at industrial scale and optimising the processes requires sophisticated bioprocess technology. This is where the art of engineering and knowledge about biology meet, with the level of knowledge of industrial biotechnology at German universities, research institutions and in industry being outstanding. Today, new findings in bioprocess engineering provide the basis for designing particularly efficient plants that are characterised by low energy requirements or high efficiency, for example. In addition, there are special requirements resulting from new production strains and organisms, such as algae.

Biorefineries are the major industrial factories of the bioeconomy. In these complex technical facilities, plant biomass is broken down into its components and utilised – analogous to a petroleum refinery. The biorefinery concept is being researched and developed at several locations across Germany *(see chapter Circular bioproduction)*.

One such research initiative is the BMEL-funded research association EthaNa, which has developed a holistic concept for rapeseed utilisation – from peeling the rapeseed to breaking down the rapeseed kernels to the fractionated extraction of oil, proteins and other ingredients. With this process, reusable rapeseed-based materials can be used for technical or cosmetic products. The process can be integrated both in conventional oil mills and in vegetable oil biorefineries.

The key challenges facing bioprocess technology are the continuous monitoring of the bio-based production process and the purification step at the end of the process chain. The industry is also looking to improve resource efficiency in order to cut costs. These are the kinds of issues investigated by a strategic alliance for knowledge-based process intelligence which is being funded by the BMBF and coordinated by Sartorius Lab Instruments GmbH & Co. KG in Göttingen for the creation of a novel sensor and software platform. Another BMBF-funded project is DigInBio, a joint project of Forschungszentrum Jülich, the Technical University of Munich and Leibniz University Hanover for the establishment of digital and automated processes in the biotechnology laboratory *(see Pharmaceutical industry)*.

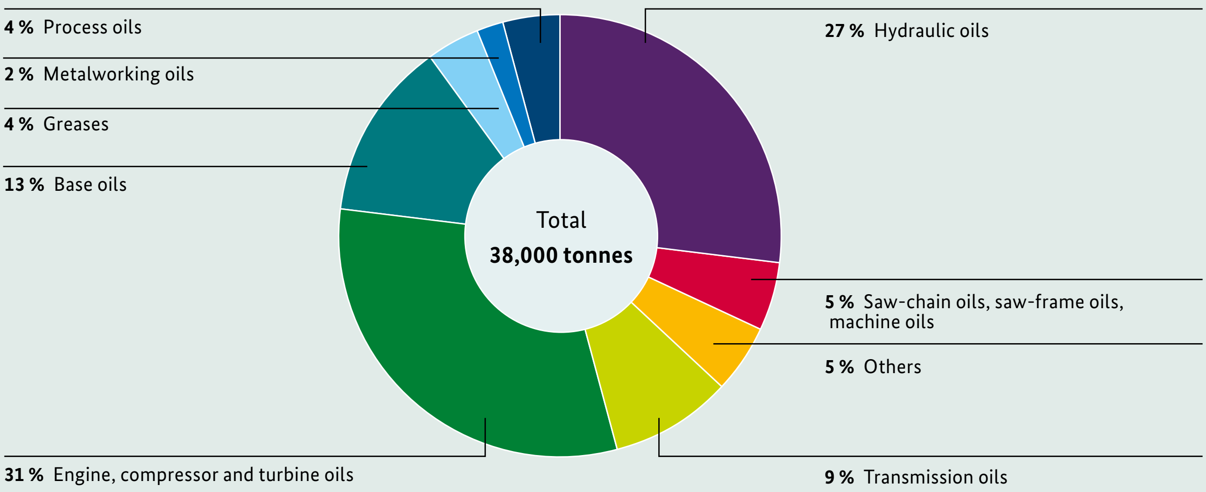
Biolubricants for machines

Today, there are products made from renewable raw materials for all lubrication and pressure transmission applications *(see chapter Chemical industry)*. These products are biodegradable, environmentally friendly and have excellent performance data. In 2020, production in Germany amounted to 38,000 tonnes *(see chart p. 60)*, with the main raw materials being palm oil, palm kernel oil and rapeseed oil, followed by animal fats. Sunflower oil and residues such as used frying fat are currently playing less of a role, but their share is growing. The BMBF-funded project ZeroCarbFP investigated ways of using enzymes to break down used frying fat from the catering industry for the production of lubricant additives. Another BMBF-funded project, PHAt, has come up with biodegradable thickeners and binding agents for lubricants and lubricating varnish from polyhydroxyalkanoates, which are naturally produced by various bacteria. The BMEL, too, launched a funding initiative in 2019 to further bio-based lubricants and hydraulic oils, which provides 6 million euros to eight collaborative projects

Innovative biogas plant technology

The heart of every biogas plant is a huge fermentation tank, or digestor, where microorganisms convert biomass from plants, liquid manure or food residues into biogas and other fermentation products. Biogas is a mixture of carbon dioxide and methane that is converted into electricity and heat on site in a combined heat and power plant. Germany is an international leader in biogas technology, with researchers working on optimising the energy yield per unit of biomass, for example by adding aggregates to the digestor. At the same time, work is ongoing to refine process and control technology and develop biogas storage systems. Other innovations concern usable raw materials, which now also include straw and other cellulosic residues. The capture and material use of carbon dioxide is also coming into focus.

Vegetable oils and fats used in the lubricant market in Germany 2020



Source: FNR (2022)

covering 31 individual projects. The goal is to develop components and additives for cooling lubricants used in metal cutting and forming, as well as thermally resilient plant-based greases for roller bearings and stationary or mobile hydraulic systems.

Manufacturing products using biomaterials

To meet the growing demand for bio-based plastics and (partially) bio-based composites, production technology has responded to the new requirements by adapting compression moulding and injection moulding processes. Forming multidimensional components presents a major challenge because wood and natural fibres have a lower density than the mineral fillers or reinforcement materials traditionally used. The BMEL-funded Biopolymernetzwerk (Biopolymer Network) responded to these challenges by investigating how the sandwich injection moulding process can be adapted to working with partially bio-based composites.

The Biopolymer Network was succeeded by the Zukunftsnetzwerk biobasierte Polymere (BioFoN) which provides a knowledge-sharing network for experts with the long-term goal of creating a fully bio-based plastics industry. Network partners work together on projects such as the development of new production processes for bio-based packaging, or for violin bows made from natural fibre composites. 3D printing is also growing in popularity across industries and is increasingly switching from traditional plastics to bio-based raw materials. One example is the production of 3-D printed wooden furniture as part of a BMEL-funded project. The construction industry is also benefitting from these new developments: For example, lightweight components made of wood or flax can be designed on a computer and manufactured by robots *(see chapter on construction)*.

Intelligent automation processes

Process plant engineering and process engineering are not the only parts of the mechanical engineering industry that could contribute to the bioeconomy. The digitalisation of all economic sectors goes hand in hand with increasing automation and intelligent networking of systems.

In the agricultural industry for example, precision agriculture has become much more important in recent years *(see chapter Agriculture and forestry)*. Mechanical engineering provides innovations in measurement and control technology as well as in automation processes that can help make agricultural processes more sustainable – both in crop cultivation and in animal husbandry.

This also includes robotics solutions such as field robots, which could be used for heavy and monotonous work in particular, or when precise work is required over a long period of time – such as fertilising or sowing. There are also some promising approaches in the cultivation of fruit and vegetables, such as watering and harvesting robots. Even delicate fruits such as strawberries or gherkins can now be picked by robots. Animal husbandry is also looking to automated solutions such as milking robots or automatic feeding systems. The machines help to use resources more efficiently, especially in large agricultural operations.

High-tech equipment can be the basis for sustainable agricultural production in greenhouses or indoor farming systems for urban farming. In indoor farming systems for example, hydroponics is combined with modern LED lighting technology, heating and ventilation systems, sensor technology and intelligent information technology in order to be able to use resources as effectively as possible *(see chapter Agriculture and forestry)*.

Food processing also relies on engineering expertise to become more resource-efficient and sustainable, with smart automation processes being in particular demand. The German Institute of Food Technologies is working on developing hygienic gripping techniques that can be used for a variety of applications. Process analytics also has an important role to play. It records and determines the quality of finished products or supplied goods and provides a system for process tracking and control, data analysis and simulation of process operations, ranging from the identification of ingredients, the recording of physical and functional properties to the tracking and tracing of food products and product evaluation by consumers.

Process technology for the circular economy

A sustainable bioeconomy works with closed material cycles which use resources more efficiently and minimise waste and emissions. Innovative, smart process technology is needed at every step of the value chain, such as product design, production and cascade use of bio-based resources (*see chapter Circular bioproduction)*. Recycling of agricultural residues and industrial waste streams has become possible through innovations in mechanical and plant engineering. The CocoaFruit project funded by the BMBF where researchers are trying to utilise the pulp and shell of the cocoa fruit, illustrates this. High-quality recycling or upcycling depends on the upstream separation and reprocessing of recyclable materials. Examples include the recovery of phosphates from sewage sludge, of building materials from demolition waste, or of balsa wood from wind turbine rotor blades.

At the Fraunhofer IVV, Susanne Naumann is researching how the shell and the pulp of the cocoa fruit can be utilised.

Food industry

The food industry is a significant element of the bioeconomy. This is where agricultural products are processed into food and animal feed. Resource-efficient technologies help to produce healthy, high-quality and safe products.

With around 6,100 companies and 614,000 employees, the food industry is one of the largest sectors in Germany. According to the Federation of German Food and Drink Industries (BVE), the total turnover in 2020 was almost 170 billion euros, which puts Germany at the top within Europe. The sector is very much characterised by small and medium-sized enterprises, with 90% of the companies employing fewer than 250 people.

Many of the operations are family businesses with a long tradition or manufacturers of regional German specialities with a strong international client base. The most important sub-sectors of the food industry are the meat and meat products industry, the dairy industry, the confectionery and bakery industry, beverage production and the processing of fruit and vegetables. The wide variety of products reflects this diversity. For the bioeconomy, the food sector is an important sub-sector. Around 80% of agricultural produce in Germany is processed into high-quality food products. Strategies for recycling waste products from the food and feed industries are becoming increasingly important.

Microorganisms as versatile refiners

Reaching into nature's toolbox to enhance our food is not a new trick. After all, *Saccharomyces cerevisiae*, or bakers' yeast, has been used for beer brewing and wine making for thousands of years. The conversion of substances with the help of microorganisms is called microbial fermentation. Lactic acid bacteria turn milk into yoghurt and other dairy products. They help to preserve food and feed, such as for example in the cases of sauerkraut or silage. For milk to become cheese, the rennet enzyme has to curdle the protein within the milk. Rennet used to be obtained from calves' stomachs. Today, tailor-made microorganisms enable biotechnological processes to take place in large steel tanks to produce these useful molecules upon which cheesemaking depends at industrial scale.

Enzymes in action

The food industry uses enzymes as natural bio-catalysts for many purposes. Since the 1960s, microbial processes inside digestors have become the standard for the production of enzymes. Around 50 different enzymes are currently being used in the food industry. About 20 companies in Germany produce enzymes, from large chemical corporations like BASF to small and medium-sized enterprises. Some of these companies receive funding from the BMBF and the Federal Ministry for Economic Affairs and Climate Action.

Enzymes are resource-efficient multi-talents that work in a very targeted manner and are mostly active under mild conditions (low temperatures, neutral pH, aqueous environment). The baking industry employs special enzymes to produce an appetising and stable bread crust. Other enzymes are added to the mix in order to add volume and colour. Pre-made dough products for baking on the premises, which have become popular in bakeries, would not even be possible without such enzymes.

Some raw materials can be enriched and used more efficiently with the help of enzymes. Pectinases, for example, help to break down the cell wall of fruit for more efficient extraction and clear turbidity in the fruit juice. Lactase splits lactose (milk sugar) into smaller molecules, which makes it another important enzyme for the food industry. Lactase is also available as tablets or in capsules to help people with lactose intolerance digest dairy products.

Flavourings and amino acids

Natural flavourings are often produced on the basis of enzymatic and microbial production processes. Strawberry flavouring, for example, originates in mushrooms, while peach flavouring is extracted from yeasts. Citric acid was the first food additive to have been produced biotechnologically on a large scale. It is no longer extracted from citrus fruit, but through a process which uses the mould *Aspergillus niger* as a cell factory and which today provides the entire global production volume (2 billion tonnes). The food industry uses citric acid, or E 330, as an additive for soft drinks, sweets, to acidify bread and in meat processing.

Another important group of food additives, amino acids, is also produced biotechnologically. These basic building blocks of proteins can provide a sweet taste, while others smell like oranges or like lemons. The salts of glutamic acid (glutamate) are used as flavour enhancers. Three million tonnes per year are produced worldwide with the help of the *bacterium Corynebacterium glutamicum*.

Technologies for safe food

Innovative technologies can help make the food chain more sustainable and resource-efficient. This includes processes for extending food shelf life or sensor systems that make food products safer for consumers. The BMEL supports a number of research initiatives in which, for example, visual methods for checking the freshness and quality of meat are being developed. The FRESH consortium is working on innovative sensor packaging that recognises the degree of freshness of fish or meat. A change in the colour of the packaging could warn consumers of microbial contamination of the packaged food.

Lupine seeds are processed in the extruder plant at the Fraunhofer Institute for Process Engineering and Packaging in Freising.

Essential amino acids such as lysine, threonine and methionine cannot be produced by organisms themselves. They are very important feed additives, with more than two million tonnes of lysine produced for the animal feed industry worldwide every year. One of the major producers of amino acids for animal feed is the specialty chemicals group Evonik.

Sweetness without all the calories

Sweeteners are a key component of many foods. In response to lifestyle diseases such obesity or diabetes, there is a trend towards lower-calory food ingredients. In particular, the demand for ingredients that taste sweet but do not contain household sugar is rising. Stevia glycosides from the tropical plant *Stevia rebaudia* are often used as a low-calory alternative as they have almost 200 times the sweetening power of normal sugar. Researchers are working on producing stevia glycosides using a biotechnological process. It is actually possible to produce highly pure individual components – such as steviosides and rebaudiosides. Unfortunately, many stevia glycosides have a metallic, slightly bitter aftertaste. To counteract this taste, c-Lecta, a biotech company from Leipzig, makes an enzyme which can be used for the production of rebaudioside M, which has no bitter aftertaste.

Brain Biotech AG, a biotechnology company from Zwingenberg which is part of the DOLCE research alliance, has identified more than 60 plant-based molecules that could be used as sugar substitutes or sweetness enhancers. Brain Biotech and the French company Roquette will bring the production of brazzein, a sweet-tasting protein extracted from a West African fruit, to industrial scale.

Brazzein was investigated as part of the strategic alliance NatLifE 2020, which was coordinated by Brain Biotech. The consortium was co-funded by the BMBF and had more than 20 partners. The objective was the joint research of natural substances that can be used as flavour changers or mask a bitter taste – such as that of the stevia sweeteners mentioned above.

Food with added benefits

Functional foods are another new trend in the food industry. Functional foods can have a positive effect on a person's health, in particular as prevention. Prebiotic substances, which include special dietary fibres, are considered functional ingredients. They can favourably affect the community of microorganisms in the gut, or microbiome. Probiotic dairy products contain live strains of bacteria that are thought to improve the balance of the microbiome when ingested. Certain secondary plant substances such as polyphenols or glucosinolates are also considered to be beneficial to health. In a BMBF-funded project, secondary plant compounds are harvested from plant residues from sweet pepper cultivation which are suitable as food supplements. Jennewein Biotechnologie (part of Chr. Hansen since 2020) receives funding from the BMBF in order to develop a biotechnical process for the production of human milk sugars to be used as an ingredient for baby food.

Protein from plants

The growing health and environmental awareness among the European population has led to rising demand for plant-based, sustainable alternatives to meat, and food producers are responding. Vegetarian and vegan meat and dairy alternatives have become mainstream. There is no other part of the food industry that is growing as strongly as that of substitutes for food of animal origin.

While plant-based products made from soy and wheat have long been used as alternative protein sources, the focus is now shifting to the domestic cultivation of protein-rich crops. Lupins are the most noticeable protein-rich crop grown in Germany on account of

Researching sustainable food of the future: the Innovation Area "NewFoodSystems"

The **Innovation Area "NewFoodSystems"** brings together players from food and nutrition research and various points on the value chain of the food industry in order to translate innovation into practice even more efficiently. The innovation area consists of almost 60 partners from science and industry and is funded with up to 20 million euros by the BMBF. NewFoodSystems is coordinated by the Max Rubner-Institut (MRI) in close cooperation with the Fraunhofer Institute for Process Engineering and Packaging (IVV). A main focus of NewFoodSystems is the systematic analysis and development of sustainable protein ingredients from higher plants, algae and insects. Coordinated by the University of Bonn, a comprehensive protein database is being created to record important product parameters, such as technofunctionality, biological value and sustainability. The idea is to make this resource available to food manufacturers looking to develop new products. Another focus is the social acceptance of innovations in food, which is investigated by the "Future Museum" of the Deutsches Museum in Nuremberg. A third focus of the innovation area are innovative approaches to indoor and vertical farming, while additional projects look into optimising insect production, the use of insects in aquaculture and a holistic evaluation of insect-based foods. Food ingredients based on microalgae are also being researched and developed, as is the indoor cultivation of spice plants and aromatic plants.
newfoodsystems.de

their colourful flowers. Lupin seeds contain around 35% of protein. For a long time, lupin seeds were shunned by the food industry because of their high content in bitter components but now researchers have been able to identify a variety that contains fewer bitter alkaloids and is very disease-resistant – the blue lupin *(Lupinus angustifolius)*. What's more, this legume is easy to grow and thrives particularly well in northern Germany. Nodule bacteria on the roots of sweet lupins bind nitrogen, which means that they also fertilise the soil.

The start-up Prolupin GmbH, a spin-off of the Fraunhofer Institute for Process Engineering and Packaging IVV in Freising, has developed a process for the extraction of lupin protein – which has a very neutral taste – from the seeds. The company was awarded the German Federal President's Award for Technology and Innovation in 2014. Based in Mecklenburg-Antepomerania, Prolupin extracts lupin protein as well as fibres, oil and shells. The latter are also suitable as food additives. The company also produces and markets its own products such as ice cream, desserts and milk substitutes.

The BMEL supports the development of plant-based protein alternatives with research funding from the Protein Crop Strategy. One example project investigates the potential of lupin varieties which are rich in bitter components as a protein source. Their high alkaloid content makes these plants more disease-resistant and easier to grow than sweet lupins. The goal of the project is to remove the bitter components using modern process engineering.

Other BMEL research initiatives aim to optimise native grain legumes such as peas for use in innovative foods. One hurdle is that the starch quality in peas varies significantly. To find out more about their starch properties, two hundred pea varieties are being cultivated as part of the research project.

Insect-based food and animal feed

Even though products based on insect proteins still occupy a small niche of the German food industry *(see chapter The resources of the bioeconomy)*, a few start-ups have started offering insect-based products. One such company is Bugfoundation, which has now become part of Kupfer Innovative Food. Bugfoundation has developed insect burgers whose patty contains large amounts of ground Buffalo worms. The Cologne-based start-up SWARM Protein started off selling fitness bars based on insect protein from crickets, but has since shifted its focus to dog food. The BMBF funds several projects exploring the potential of insect-based products for food and animal feed.

This work is carried out by the Innovation Area "NewFoodSystems" *(see box on p. 65)* as well as several consortia within the funding initiative Agricultural Systems of the Future. The food4future collaboration project tests the breeding of crickets for urban food production, while the CUBES Circle network pursues the vision of intelligent networking of different agricultural production systems for plants, insects and fish in closed energy and material cycles. The network feeds the larvae of the soldier fly, which are ideal re-


Lupine seeds are particularly rich in protein. Their use in meat substitutes such as burger patties is being tested at the Fraunhofer IVV.

cyclers of food waste or other by-products of the food industry, to silver carp and tilapia.

Upcycling: recycling residues

There are a number of bioeconomy research projects working on recycling food industry waste within a bio-based circular economy. Upcycling offers companies in the food industry a great way of developing a range of new products with added value from these sidestreams.

One such project is the BMBF-funded CocoaFruit consortium, which is coordinated by Fraunhofer IVV in Freising *(see photo p. 61)* and based on a cooperation with Indonesian partners and German companies. The goal is to use every part of the cocoa fruit and to develop innovative foods and ingredients from it. The cocoa beans – the basis of chocolate – only make up 10% of the cocoa fruit. The remaining 90%, the shells and pulp, are hardly used. One idea is to use the cocoa shells as a substrate for the cultivation of mushrooms to be used for the production of sausage substitute products. The pulp is used as a basis of fruit preparations and beverages. Upcycling concepts also include alcoholic spirits made from whey, snacks made from excess fruit and beer made from discarded bread.

Meat and cheese from the laboratory

Industrial meat production uses up enormous resources, which damages the climate and the environment. There are also ethical concerns and concerns about animal welfare. Innovative cell culture technology offers new options for more sustainable food production. More and more researchers and companies are considering the production of meat and fish from cell culture (cultured meat). Meat is usually grown from muscle stem cells or other cells that are capable of reproduction in a bioreactor. Innovative players in Germany include the Rostock-based start-up Innocent Meat and the Berlin-based start-up Bluu Seafood. Berlin-based start-up Formo wants to conquer the market with vegan mozzarella and other substitute dairy products (photo). They have developed a biotechnological process using yeasts to produce casein and whey protein – the molecules responsible for the taste and texture of dairy products – in the laboratory. The start-up uses these molecules to produce various cheese substitutes based on vegetable fats.

Pharmaceutical industry

Medicinal herbs have been used against illnesses for thousands of years. Today, medicines are more and more often produced using biotechnological processes. Biopharmaceuticals, which include active ingredients such as antibodies, enzymes and vaccines, account for about one third of the pharmaceutical market – and their share is growing rapidly.

Pharmaceutical companies are increasingly resorting to knowledge about biology for the production of medicines. Although chemically synthesised active ingredients still make up the largest share of the German pharmaceutical market, so-called biopharmaceuticals are catching up. Biopharmaceuticals are biomolecules that are too large to be produced chemically, or at least their production would not be efficient. This is where modern biotechnology comes in by using molecular genetic processes that turn living microorganisms and cells of higher living organisms into miniature factories for drugs.

According to an industry report published by the Boston Consulting Group and vfa bio, at the end of 2020, 339 biopharmaceuticals had been approved in Germany. This pushed the market share of these biotechnologically produced medicines to almost 31%. In 2020, a total of 14.6 billion euros was generated with biopharmaceuticals in Germany, including antibodies against cancer or autoimmune diseases such as rheumatism or multiple sclerosis, hormones such as insulin for the treatment of diabetes or enzymes against metabolic diseases.

Biotech drugs are on the rise

Genetically engineered drugs for humans and animals are widely accepted by society. In 2020 alone, 25 more biopharmaceuticals were approved. The largest players are the former Hoechst site in Frankfurt, which is now part of the French company Sanofi, and the Swiss pharmaceutical company Roche, which has established extensive production capacities for biotech drugs at its Penzberg site. In addition, some German companies have large-scale production facilities, for example Bayer in Leverkusen, Merck in Darmstadt and Boehringer Ingelheim in Biberach. A number of small and medium-sized biotechnology companies have specialised in taking over bio-based production as service providers or in helping to develop and implement processes that meet market requirements. In 2020, the total production capacity for biopharmaceuticals in Germany was estimated to be 380,000 litres. Germany ranks fifth worldwide behind the USA, South Korea, Ireland and Switzerland. When it comes to the biotechnological production of active pharmaceutical ingredients, Germany is one of the world leaders.

Antibodies, peptides, vaccines

Among biopharmaceuticals, antibodies in particular have come into focus. These complex protein molecules are considered the "sentry guns" and guided weapons within the human immune system. Each specific antibody will attach to a specific molecule only, such as the surface protein of a virus or the toxin of a bacterium. Antibodies bind to their target molecule, marking it for degradation. Antibodies are produced using cell cultures. At the end of 2020, 107 antibody-based medicines had been approved, which is 32% of all approved biopharmaceuticals. Especially the treatment of cancer and autoimmune diseases has seen considerable improvement since the advent of antibody therapy. The sales of antibody drugs in Germany were at 10 billion euros.

Peptides are small protein molecules composed of up to 100 amino acids. The pharmaceutical and cosmetics industries use peptides as active ingredients or bioactive ingredients for creams and ointments. Numaferm, a company based in Düsseldorf, has developed a biotechnical process for the large-scale production of peptides with the help of microorganisms. The start-up was funded by the BMBF on several occasions.

Other classes of drugs, such as antibiotics and vaccines, are also usually produced with biotechnology. German vaccine production focuses on influenza, tick-borne encephalitis (TBE), diphtheria, whooping cough, rabies, Ebola and, since 2020, COVID-19.

The COVID-19 pandemic has given a boost to vaccine research and production. Mainz-based company BioNTech has commissioned an innovative facility for the production of mRNA vaccines against COVID-19 in Marburg. The production of mRNA vaccines is cell-free, meaning that no living cells are used for production. The biomolecules and all necessary components are synthesised in a reaction vessel.

Intelligent bioprocesses

We need intelligent bioprocess technology for the efficient production of all these medicines in the required quantities *(see chapter Mechanical engineering)*. Thanks to Germany's technical expertise, the country is a leader in bioprocess engineering. The BMBF is supporting companies so they can continue

The digitalised biotech laboratory

The collaborative project DigInBio aims to highlight the opportunities presented by digitalisation, automation and miniaturisation for industrial biotechnology, and to make use of them. The partners in this BMBF-funded project work across three digitalised bioprocess laboratories that are connected through a central data management system. The focus is on various steps in bioprocess development. From intelligent software components to knowledge-based experiment planning, to sequence control of real-time simultaneous laboratory experiments, to online data evaluation, in order to be able to drastically shorten bioprocess development in the future. The project partners of DigInBio are Forschungszentrum Jülich, the Technical University of Munich and Leibniz University Hanover.

The biotechnology company Eleva produces biopharmaceuticals in the moss bioreactor.

to overcome challenges in this field, such as the need for optimised process control based on intelligent sensor technology. Around 20 partners of the strategic alliance “Knowledge-based Process Intelligence” have developed a sensor and software platform that combines novel measurement principles with modern data evaluation. Another central issue which receives funding from the BMBF is the continuous improvement of purification for biotechnologically produced medicines.

Suitable production organisms are also an important research focus. While in the early days, biotechnology mainly concentrated on working with bacteria – as in the case of insulin – the focus has now shifted to mammalian cells, such as CHO cells (originally from hamsters), or human cell lines. Unlike bacteria, these cells are able to produce certain molecules that determine the effect of drugs. A BMBF funding initiative is looking to establish new microbial biofactories for the industrial bioeconomy, especially for active pharmaceutical ingredients such as terpenes or isoprenoids.

Green pharmaceutical producers

Today, biological drugs are also made from unconventional organisms. There is increasing interest in using plants to produce innovative active substances. Back in 2012, the US Food and Drug Administration (FDA) approved an enzyme produced in carrot cells for the treatment of Gaucher disease. In Germany, too, research is being conducted into so-called molecular farming as an approach to plant biotechnology.

Scientists at the Fraunhofer-Institute for Molecular Biology and Applied Ecology in Aachen use tobacco plants as green pharmaceutical factories, using an automated production plant. From sowing, cultivation in a high rack system with controllable lighting, irrigation and fertilisation, to harvesting and biotechnological production, practically every step is automated. Based on a process developed by the Halle-based biotech company Icon Genetics, a new plant-based cancer vaccine against lymphoma is to be produced under controlled conditions in the greenhouse.

Research carried out by plant researchers at the University of Freiburg is providing the basis for a production process for drugs based on the spreading earthmoss *Physcomitrium patens* that is being developed by Eleva (formerly Greenovation), a biotech company.

Some plants contain potentially interesting medically active substances, such as paclitaxel, a substance derived from the Pacific yew (*Taxus brevifolia*), which is used as a cancer drug. Since the population of the Pacific yew is small and the concentration of active substance is low, the global demand for paclitaxel could not be met using traditional methods.

To meet demand, a semisynthetical process from certain plant-based sourcing materials was used for many years. In 2002, the British pharmaceutical company Bristol-Myers Squibb developed a process in which the active substance was isolated from yew cells cultivated on nutrient media in digestors. Biotechnological production takes place at Phyton Biotech GmbH in Ahrensburg, Schleswig-Holstein, which has one of the world's largest plant cell-based digestor capacities.

Upholding the tradition of medicinal plants

In addition to modern, biotechnologically produced pharmaceuticals, traditional medicinal plants still play an important role today. The cultivation of medicinal herbs has a long history in Germany, which has 440 native medicinal plants. About 75 of them are grown commercially on an area of about 12,000 hectares, mainly in Thuringia, Bavaria, Hesse and Lower Saxony, and account for more than 70% of domestic medicinal plant cultivation. Chamomile has the largest share (more than 1,000 hectares), followed by linseed, milk thistle, peppermint and sea-buckthorn (500 to 1,000 hectares each). However, domestic cultivation is only a niche, because around 85% of medicinal plants processed in Germany are imported.

Plants for which demand is low or that do not grow in Germany are collected in their natural habitat through wild harvesting. Unlike in commercially cultivated plants, these plants may vary in terms of quality and quantity of their compounds. This is why there are growing attempts to cultivate plants that are still only found in the wild. However, this is not easy. The time it takes before harvesting is possible is long – at least five years for herbs, and even longer for some woody plants. For this reason, the BMEL supports research work on the cultivation of medicinal plants *(see box p. 71)*.

Promoting the cultivation of medicinal plants

The BMEL is supporting a junior research group at the Julius Kühn Institute in Quedlinburg that is investigating St. John's wort (photo) and aniseed. The researchers want to make the cultivation of these plants economically viable and answer questions about phytopathology and plant protection. The major cost factor in medicinal plant production is drying. In a BMEL-funded project, researchers from Hohenheim and Potsdam are developing a practical, energy-efficient and cost-effective dryer for medicinal plants that is suitable for use in small and large-scale operations.

Consumer goods

Whether cosmetics, dishwashing and washing detergents or household appliances – a wide range of bio-based processes are already used in the production of everyday products. They enable the development of innovative consumer products with new features. Bio-based packaging solutions are also becoming increasingly popular.

According to the Federal Statistical Office, private consumption in Germany amounts to around 31,000 euros per household. With around 14 billion euros, clothing and food as well as personal care and hygiene products accounted for the largest shares of private consumption in Germany in 2020. Around 4.6 billion euros were spent on detergents and cleaning products. The bioeconomy has been an intrinsic part of the consumer goods industry for some time. Many industrial manufacturing processes rely on natural raw materials or bio-based processes.

The latter are already particularly prevalent in the production of detergents, care products and cleaning agents, with more than one third of all ingredients (total of 525,000 tonnes) having been fully, or partially, bio-based in 2019 (IKW Sustainability Report). These ingredients include surfactants, alcoholic solvents, enzymes and citric acid. The entire production of citric acid today is already based on fermentation using moulds with molasses, a by-product of sugar beet processing, as the substrate.

Surfactants from vegetable oils and microbes

Surfactants are indispensable components of cleaning agents, detergents and cleaning products that are produced either from petrochemical, or from renewable raw materials. Mixed surfactant systems consist of both petrochemical and bio-based raw materials, mainly vegetable oils and animal fats *(see chart p. 74)*. Most surfactants produced through chemical synthesis are based on palm kernel or coconut oil. According to the digital platform Forum Waschen, the amount of coconut oil used in the production of surfactants for detergents, care products and cleaning agents in Germany was estimated at 14,000 tonnes in 2017. The share of palm kernel oil reported by the Forum for Sustainable Palm Oil was 75,000 tonnes in 2019. To reduce the impact on the environment, German producers have been turning to European oil crops such as rapeseed, olive, linseed and sunflower, or to sustainably produced tropical oils.

Biosurfactants are surfactant molecules that are biotechnologically produced using microorganisms or enzymes. While there are only a few products containing biosurfactants on the market, their potential is thought to be considerable. Specialty chemicals group Evonik is among the pioneers in the field of rhamnolipids, a type of biosurfactant naturally produced by bacteria. Biotensidion is a start-up based in Karlsruhe which develops biosurfactants. The strategic Innovation Alliance for Functionally Optimised Biosurfactants aims to promote the biotechnological production of biosurfactants from domestic renewable raw materials. The BMBF has been funding the alliance since 2018 as part of the Innovation Initiative Industrial Biotechnology with 6.4 million euros over a period of six years. Research institutions and companies have joined forces to cover the entire value chain of biosurfactant production.

The consortium includes BASF, Henkel, Festo and Analyticon Discovery and is coordinated by Dalli-Werke, a cleaning products and cosmetics manufacturer. The alliance is looking to develop a wide portfolio of different biosurfactants for many application areas (such as detergents and cleaning agents, cosmetics, crop protection and food), and to boost productivity and make the process scalable.

Microalgae extracts for the cosmetics industry

Microalgae contain numerous natural ingredients that are interesting for the cosmetics industry. They can be easily propagated in bioreactors through light irradiation and carbon dioxide gassing. Up until now, microalgae are hardly used as industrial production systems. This also applies to the green algae *Tetradesmus wisconsinensis*, which has recently been made accessible for the production of carotenoid canthaxanthin in the TEWICOS project. The BMBF-funded SME innovation project has managed to use antioxidant to bind free radicals, thus reducing cell damage due to UV radiation, which accelerates skin ageing. These molecules from microalgae extracts could be used in cosmeceuticals, or active cosmetics. A research team from Hochschule Anhalt University of Applied Sciences and Salata AG in Potsdam are involved in the project.

Enzymes – effective cleaning aids

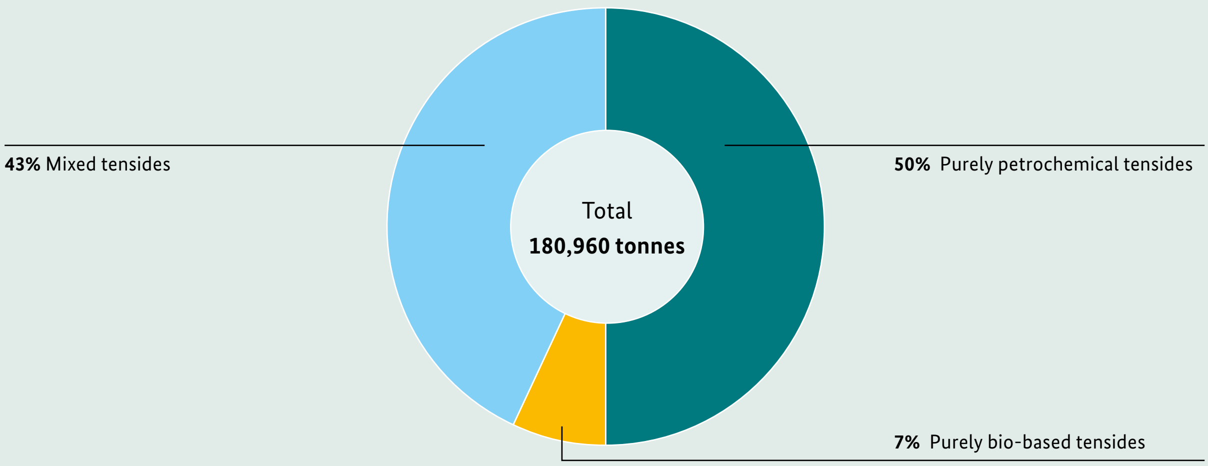
Next to bio-based surfactants, microbially produced enzymes are essential ingredients of detergents and cleaning agents. This segment of the consumer goods industry accounts for the largest market share (40%) of industrial enzymes. The use of these biocatalysts in detergents over many years has certainly helped to save water and energy, making laundry management much more environmentally friendly. Since enzymes are often active at moderate temperatures, it has become possible to reduce the average washing temperature to 46 °C from 63 °C in 1972.

Today only 7% of all washes are at 90 °C, compared to about 40% more than 40 years ago. Biocatalysts have also increased the efficiency of detergents: While in the past 220 grams were needed for a 5-kilogram wash, today 75 grams are sufficient. According to the German Cosmetic, Toiletry, Perfumery and Detergent Association, around 7,100 tonnes of enzymes were used as ingredients in detergents and cleaning products in 2019, compared to only half that amount in 1994.

Bioactive molecules for cosmetics

In response to a growing demand for natural cosmetics, manufacturers have been using special bioactive

Share of the different surfactant groups in detergents and care products in Germany 2017



Source: FNR (2020) based on T+I Consulting (2017)

ingredients in personal care products for some time now. According to the Federal Statistical Office, 34% of Germans much prefer natural personal care products without chemical additives, which is why more and more cosmetics producers are using natural and sustainable raw materials and active ingredients.

Microorganisms or cells are used as living biofactories in biotechnical production. Bioactive ingredients that are biotechnologically produced include peptides, lipids, vitamins and sugars or enzymes. Brain, a biotechnology company from Zwingenberg, uses bacteria to produce the preservative perillic acid from terpene derived from orange peel. In 2018, fragrance and flavour manufacturer Symrise from Holzminden introduced a pentylene glycol which is derived from bagasse, a by-product of sugar cane processing. The green alternative is the result of a collaboration with the Leibniz Institute for Catalysis at the University of Rostock. Another strategic alliance funded by the BMBF develops bio-based cosmetics: GOBI - Good Bacteria and Bioactives in Industry bundles research findings on the health-promoting effects of living microorganisms and makes the information accessible for industrial application. The network is coordinated by the biotechnology company Novozymes Berlin (formerly Organobalance).

Bio-based materials for products

Plastics are key materials for the consumer goods industry. However, plastic waste mountains and microplastics in the food chain have brought us to the realisation that plastic products and packaging are actually a global challenge. This is why bio-based and biodegradable alternatives are receiving more and more interest *(see chapter Chemical industry)*. The range of products for which these alternatives are being investigated goes from electrical goods to office supplies to sports equipment. Tecnaro, a Fraunhofer spin-off, specialises in plastics made from renewable raw materials. With the support of the BMBF, amongst others, the company has developed a thermoplastic bioplastic, ARBOFORM. This “liquid wood” can be used to produce a wide variety of products, including toy figures or storage boxes. In another project funded by the BMEL, FKuR Kunststoff has joined forces with several research institutions to develop new bio-based hard-soft composite materials that can be processed using multi-component injection moulding to make office equipment, personal care items and sports equipment as well as handles and housings. The hard phase of the new material consists of cellulose acetate (CA) and polylactic acid (polylactide - PLA), while the soft phase is based on termoplastic elastomers (Bio-TPE) and bio-based ethylene propylene diene monomer rubber (Bio-EPDM).

Innovative packaging

New EU plastics directives and corresponding national laws as well as consumer pressure are forcing companies to optimise packaging materials in terms of recycling, recyclability and sustainability. In the food and pharmaceutical sectors in particular, the requirements for packaging are very high because they need to be robust and protect the contents from dirt, moisture and microbial contamination, while preferably also being recyclable. For bio-based plastics to meet these requirements, the BMEL is funding several application-oriented research approaches. The BioPrima project by Südzucker AG and its partners is developing a starch-based shrink film that is suitable for freezing. The Fraunhofer Institute for Process Engineering and Packaging IVV and the Albstadt-Sigmaringen University are working on a bio-based and recyclable packaging concept for sensitive food that is packaged in a protective gas atmosphere. The Fraunhofer Institute for Silicate Research ISC is working with industry partners to develop bio-based high-performance barrier films that are 95 to 100% bio-based and recyclable.

Industry demand for paper-based packaging is also high. Two projects funded under the BMBF ideas competition New Products for the Bioeconomy are developing innovative solutions for this. One of the projects is the BioBox, made entirely of innovative wrapped paper with the required barrier properties for protecting the content. Another project is testing thermoformable paper materials to produce three-dimensional structures. There are some companies that have started making paper from grass fibre, as an alternative to wood. Agricultural residues can also be used as a source of fibre. The cleantech start-up BIO-LUTIONS from Hamburg is working with Zelfo Technology GmbH to develop a mechanical process for the extraction of fibre from wheat straw, rapeseed straw, reeds and vegetable stalks. The resulting fibre pulp can be pressed into a variety of shapes, for example for packaging and tableware. A production facility is currently being built in Schwedt, Brandenburg.

The company BIO-LUTIONS produces packaging from agricultural residues such as wheat straw or vegetable stalks.

Textiles

The textile industry has always used renewable raw materials, from plant fibres such as linen or cotton to animal products such as wool, silk or leather. With the increasing drive towards more sustainability, bio-based innovations are on the rise. Examples include biotech silk, vegan leather and vegetable tanning and dyeing agents.

Clothing has been produced from natural products for thousands of years. The manufacture of linen fabrics from flax fibres goes back as far as the ancient Egyptians and Romans. Inexpensive, petroleum-based synthetic fibres have only become established in recent decades. According to the Industrievereinigung Chemiefaser e.V. (Industrial Association Synthetic Fibres), around 108 million tonnes of textile fibres were produced worldwide in 2020. Natural fibres account for 25%, while synthetic fibres make up 75% of global production. Cotton is by far the most commonly used natural fibre for home and clothing textiles. The entire plant can be utilised: seed fibres for making textiles, cotton oil for cosmetics and plant residues as green manure.

Unlike other textile plants such as flax, hemp or jute, the stalks of cotton plants are also processed. However, global production of these bast fibres is much lower, at around 2 million tonnes per year each. Although they can be processed like cotton, they are mainly used for so-called technical textiles in industrial applications rather than the production of clothing. The huge global demand for fabric can no longer be met by cotton. In 1990, the worldwide availability of cotton was 19 million tonnes, which is 49% of the total fibre market. According to the Industrievereinigung Chemiefaser (Industrial Association Synthetic Fibres), the 26 million tonnes of cotton produced in 2020 covered just under 24% of total fibre production worldwide.

Textile production is resource-intensive and not yet very sustainable, no matter whether it uses natural or synthetic fibres. While synthetic fibres are largely petroleum-based and not easily biodegradable, cotton production consumes large amounts of water and uses massive amounts of pesticides. But textiles use up a lot of resources and damage the environment during their entire life cycle, as the life cycle assessment of a T-shirt carried out by researchers at the TU Berlin reveals. In addition to production, distribution and disposal, washing has the biggest impact on the footprint and uses large amounts of energy and water.

Innovative fibres made from wood and milk

There are synthetic fibres that are based on a renewable raw material – wood. Cellulose regenerated fibres are obtained from cellulose, which is then chemically modified, such as viscose. Even though viscose is chemically identical to cotton fibres, viscose fibres have a wider range of possible fibre geometries (length, crimp, fineness, cross-sectional shape) and can thus be applied more widely. While the production and processing of viscose consumes less energy and water than cotton, it produces toxins such as hydrogen sulphide (H_2S) and carbon disulphide (CS_2) that are harmful to human beings and the environment.

There are other synthetic fibres made from cellulose whose production is less environmentally harmful, such as lyocell. The direct dissolving process relies on a non-toxic solvent and works within a closed material cycle. The cellulose for lyocell fibres is harvested from eucalyptus or beech wood. These plants grow faster than cotton and have a high yield per area, which gives them a better environmental footprint. Recent research has also shown that flax, hemp, bamboo, banana and soya are also suitable for cellulose pulp.

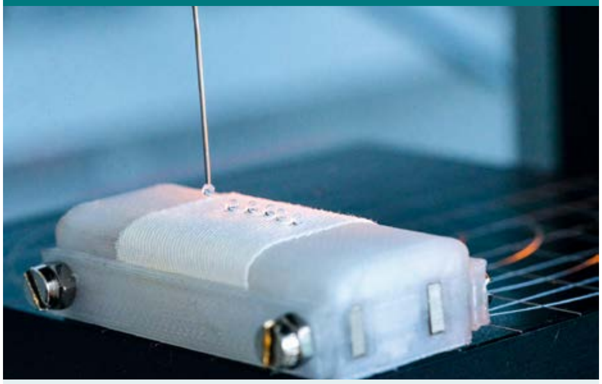
The German Institutes of Textile and Fiber Research Denkendorf (DITF) have developed an innovative material made of pure cellulose named purcell. Both the matrix and the reinforcing fibre embedded in this one-component composite material are made of cellulose. This enables an eco-friendly recycling concept with a low environmental impact and carbon footprint. Purcell is manufactured using a novel technology based on ionic liquids. The Federal Ministry for Economic Affairs and Climate Action has supported the DITF researchers.

Even waste from the food industry can now be used for textile production. Hanover-based Qmilk Deutschland, for example, produces a biopolymer consisting of the milk protein casein from non-marketable raw milk. The fibres are produced without chemical additives and can be used to make clothing or technical textiles for medical devices or the automotive industry.

Biotech silk fibres

Spider silk threads are marvels of nature; they are only a tenth as thick as a human hair, yet twenty times stronger than steel and more elastic than rubber. The natural material is extremely suitable for

Finishing textiles with enzymes and biopolymers



Enzymes are used as bio-catalysts for processing or finishing fabrics, for example for bleaching or for achieving the stonewashed effect in denim. Textiles made of synthetic fibres are a challenge for manufacturers, as they form unwelcome pilling on the textile surface after repeated washing. During the FuPol project funded by the BMBF, a strategic alliance including detergent manufacturer Henkel conducted research on how to reduce pilling. The enzyme cutinase was able to reduce pilling and improve the dyeing result at the same time. Not only enzymes, but also biopolymers are being considered for finishing textiles. The ChitoTex research project, led by Fraunhofer IGB and supported by the BMBF, has found a way to coat textile fibres with chitosan in order to make them water-repellent (photo). The biopolymer was extracted from insect skins and could replace previously used chemicals.

Bio-based innovation for the textile industry – the BIOTEXFUTURE innovation space

The BIOTEXFUTURE innovation space aims to make the entire value chain of the textile industry more sustainable. To this end, the innovation space provides a network for 75 companies, research institutions and universities. With up to 20 million euros funding from the BMBF, numerous projects are dedicated to the production of bio-based textiles based on sustainable raw material cycles. Project partners include the sporting goods manufacturer adidas, Fraunhofer IGB, RWTH Aachen University and the University of Bayreuth. The Algaetex project uses microalgae as a raw material for plastic yarns that could potentially be used to make T-shirts and knitted shoe uppers *(see photo)*. Another project is developing a bio-based coating that is water-repellent, antimicrobial and dries faster. The BIOBASE project has set itself the goal of replacing one petroleum-based product with a product made from biopolymers in each of the following areas: automotive, sportswear, interior design and technical textiles. The close ties between the project partners are intended to contribute to consolidating all options along the entire value chain.

biotexfuture.de

high-tech textiles. The Martinsried-based company AMSilk has developed a biotechnological process to produce spider silk protein on an industrial scale. The company, founded in 2008 as a spin-off from the TUM in Munich, has converted bacteria into cell factories for spider silk protein. The final step of the bioprocess is a white protein powder that can be spun into fibres by machines *(see photo on p. 79)*. Textiles made from these vegan silk biopolymers are not only particularly hard-wearing and skin-friendly, but also completely biodegradable. Sports clothing company adidas has joined forces with AMSilk and produced a sneaker prototype whose upper material consists of Biosteel fibres *(see photo p.78)*. These biotech textiles have also been used in straps by watch manufacturer Omega.

Vegan leather and eco-friendly tannins

Leather is a durable and versatile material that is used for many everyday objects, such as furniture and clothing. However, leather made from tanned animal hides causes pollution and is viewed with increasing scepticism. Consumers are turning to imitation leather made from pineapple fibre, apple pomace or cactus leather, which are considered to be more sustainable. However, these materials always contain some petroleum-based plastics, such as polyvinyl chloride or polyurethane. Another new alternative are leather substitutes made from fungi which are cultivated on residues from agriculture and forestry, such as sawdust or molasses. The growing fungal network, the mycelium, creates fungal biomass, which can be processed into a material that looks and feels almost exactly like leather. Some biotechnology companies have already started marketing the materials obtained from fungi. adidas for example has produced a prototype of a vegan sports shoe using a fungal mycelium material called Mylo instead of leather. It is manufactured by the US company Bolt Threads from California. The Leipzig-based start-up ScobyTec has also developed a biotechnical process in which microorganisms produce bacterial nanocellulose (BNC), a nonwoven fabric that can be used instead of leather.

There are also some bio-based innovations in leather tanning. Chromium salts, which are harmful to the environment and health, are increasingly being replaced by plant-based tanning processes. One example is Rhubarb Technology, a start-up that has extracted a substance suitable as a tanning agent from the roots of rhubarb plants. wet-green, a company from Reutlingen, makes a tanning agent from olive leaves, which was developed in collaboration with N-Zyme BioTec. Textile dyeing is also turning to plant-based raw materials, using traditional plant dyes in order to make textile dyeing more sustainable. Dyeing plants such as madder, reseda, bluewood, gardenia and jasmine flowers have proven to provide effective dyes. In a project funded by the BMEL, two vegetable dyes for printing on silk and modal fabrics were developed. The spring 2019 collection of hessnatur already featured two silk blouses that had been printed using the colour pastes developed in the project.

Recycling challenge

According to the Bundesverband Sekundärrohstoffe und Entsorgung e. V. (BVSE - German Association for Secondary Raw Materials and Waste Disposal), approximately one million tonnes of clothing end up in clothing banks every year. Clothes that are no longer wearable are usually turned into cleaning rags or painter's fleece. However, a sustainable circular economy in which textile fibres are recycled has not yet been created. Researchers at Fraunhofer IAP have found a way to produce a high-quality fibre from used cotton textiles. This had previously not been technically feasible because most clothes are made of mixed fibres. The researchers have developed a process for filtering cellulose from the cotton to create a viscose filament yarn consisting of 100% cellulose. The quality of these recycled fibres is comparable to wood-based cellulose regenerated fibres and has the same quality as viscose fibres.

Knowing each type of fibre and understanding the fibre composition is a prerequisite for recycling textiles. The DiTex project is testing the quality, resources and sustainability of workwear and towels made from recycled fibres as part of a pilot project funded by the BMBF. For this purpose, the textiles were equipped with an intelligent label that stores parameters such as material mix, fibre origin as well as washing and recycling cycles. This allows tracking and analysing the complete life cycle of the textiles, including all environmental aspects.

AMSilk produces textile fibres from microbially produced spider silk proteins (left). Imitation leather made from bacterial nanocellulose by ScobyTec (right).

The social dialogue

Establishing a bioeconomy is a process that involves society as a whole. For a bio-based, sustainable economy to become a reality, the objectives and possible conflicts of objectives need to be discussed with all stakeholders.

An increasing number of organisations, institutions and bodies are dedicated to shaping, promoting and critiquing the bioeconomy. This is happening at all levels of society.

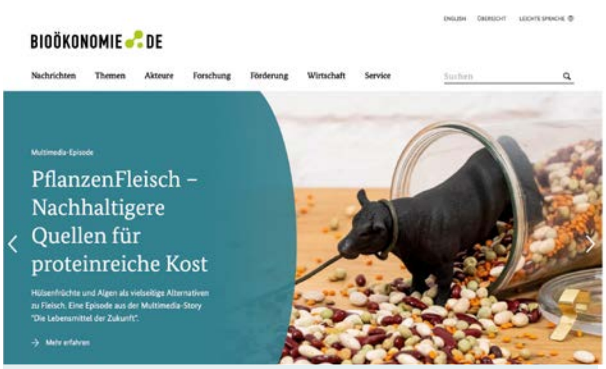
As this brochure shows, the bioeconomy is taking hold in many economic and industrial sectors and many scientific disciplines are working on it, including life sciences and chemistry, but also economics, politics and social sciences. Media, art and culture are also increasingly engaging with the concept of the bioeconomy, which does not just concern politics, economics and science but is actually happening in people's lives. This leads to the logical conclusion that everyone should be able to join the debate on the bioeconomy, and that as many people as possible should contribute to creating a bio-based economy. While the awareness of sustainability and climate change in politics and society has grown, the concept of the bioeconomy is complex and difficult to grasp. Surveys have shown that debates in connection with the bioeconomy have not yet been fully embraced by the population, and that society is only just beginning to form opinions on the bioeconomy. The vision of a bio-based economy needs explanations on many levels.

Social dialogue and a grasp of the challenges and opportunities of the bioeconomy have a key role to play in the transformation towards a bio-based economy. In this context, the demand for new products and services and the associated innovations and technological developments are important factors. The bio-based economy will only stand a chance if citizens are actively involved in shaping this societal change.

For this to happen, the opportunities and risks have to become more visible, which in turn requires clear communication on research and innovation as well as the latest developments. The information portals bioökonomie.de and Pflanzenforschung.de *(see box and further links)* are important contributions to expert communication of key aspects of the bioeconomy, making interesting topics on bio-based management and plant research accessible to the public.

The Federal Government's National Bioeconomy Strategy aims to discuss and evaluate important topics and potentials, as well as risks and possible conflicts of objectives with all stakeholders. Resolving or balancing these conflicts of objectives is a prerequisite for attaining the UN Sustainable Development Goals *(see chapter Aiming for a sustainable bioeconomy)*. This is why the Bioeconomy Strategy emphasises the importance of using various formats of transparent dialogue and participation processes to involve civil society.

Information platform biooekonomie.de



The main source of information for anyone wanting to learn about the bioeconomy in Germany or anywhere in the world is the information portal biooekonomie.de. Launched by the BMBF, the website features news, interviews, showcase bio-projects as well as in-depth reports and multimedia stories in an accessible manner. The website also provides an overview of the bioeconomy worldwide and ongoing funding initiatives. It gives access to databases on research institutions and funding initiatives and more than one hundred videos. In the German-language "Actors" section, under "Bio-pioniere", important players of the bioeconomy are introduced through videos, podcasts and text-photo reports. bioökonomie.de also conceptualises exhibitions and exhibits, such as NaturFutur – Bioökonomie erleben (Future of Nature – Exploring the Bioeconomy), which was on display at the Museum für Naturkunde – Leibniz Institute for Evolution and Biodiversity Science in Berlin in November 2021.

biooekonomie.de

Testing different formats of dialogue

The overarching BMBF Program Bioeconomy and Societal Change provides funding for awareness campaigns highlighting the opportunities of a societal transformation towards a bio-based economy. This includes initiating a public debate on the objectives of the bioeconomy and a sustainable economy and way of life. The ideas competition Neue Formate der Kommunikation und Partizipation in der Bioökonomie (New formats of communication and participation in the bioeconomy) launched in 2016 is a funding module under the above-mentioned umbrella concept which brought together various players from the worlds of science, business and general society.

The competition was aimed at highlighting the concerns and objectives of the bioeconomy while gathering new insights into weaknesses in the argumentation for a bioeconomy and acceptable implementation strategies. The BioKompass project, for example, explored different bioeconomy scenarios through various dialogue formats, while the BioDisKo project focused on participatory dialogue and regional discourse on different pathways within the bioeconomy in North Rhine-Westphalia.

As with all processes of profound change, it is important that gut reactions and concerns be addressed early on and that an adequate public debate is supported. The BMEL is using roundtable discussions as one way of achieving this and runs the Borchert Commission (Borchert-Kommission, the commission on improvements in livestock farming), the Partnerschaft Umwelt und Landwirtschaft (Environment and Agriculture Partnership), the Praktikernetzwerk (Practitioners' Network) and the Scientific Advisory Boards on Agricultural Policy, Food and Consumer Health Protection; Biodiversity and Genetic Resources; and Forest Policy.

To encourage young people to engage in a discourse on renewable raw materials, the BMEL is funding a project entitled Einfach wachsen lassen! (Just Let it Grow!) The conflicts of objectives around forest use are addressed in the MorgenWald project (The Forest of Tomorrow), an experiential and interactive participation format fostering debate about the future of forests. In 2020, the Federal Ministry of the Environment funded the Bürgerdialog zu Chancen und Risiken der Bioökonomie für die biologische Vielfalt (Citizens' Dialogue on the Opportunities and Risks of the Bioeconomy for Biodiversity), which was based on four workshops representing the starting point for a discussion held in a subsequent online dialogue.

Science Year 2020/21 – Bioeconomy

The launch of the National Bioeconomy Strategy more or less coincided with the start of the Science Year dedicated to the bioeconomy in January 2020. This initiative by the German Federal Ministry of Education and Research and the organisation Wissenschaft im Dialog (Science in Dialogue, WiD) was officially opened at the Futurium on Berlin's Alexanderufer. A few weeks later, the COVID-19 pandemic struck and changed all plans for the Science Year, which was therefore extended to 2021. The Science Year as a platform for dialogue between research and society at large was able to showcase the bioeconomy. At numerous events, such as exhibitions, competitions and roundtable discussions, protagonists from the worlds of science, the economy, education, culture and politics across Germany advocated critical debate on science and controversial discussions. The Science Years are also perceived as drivers of science communication, for instance through a total of 32 innovative science communication projects funded by the BMBF during the Science Year 2020/21 – Bioeconomy. Due to the pandemic, many projects were moved online or designed as online events.

The funded projects ranged from creative formats (poetry & science slams, podcasts, design fiction) to educational games (geocaching, video challenges, gaming), and some encouraged people to become actively involved (tastings, experimental workshops, election arenas). Press releases, opinion pieces from researchers, information about funded projects and an events calendar were all featured on the website wissenschaftsjahr.de. The website also offered games, short information videos and do-it-yourself instructions. Wissenschaft im Dialog (Science in Dialogue, WiD) organised debates, a university competition *(see chapter on careers)*, online events on sustainable fashion (Hack Your Fashion) and toured the country with a mobile Escape Room. The exhibition ship MS Wissenschaft acted as a floating science centre travelling Germany's waterways during the summer months and stopped at 30 locations. The Citizen Science initiative Expedition Erdreich (Soil Expedition) was all about citizens researching soil health. The project revolved around the tea bag protocol, which can be used to see how quickly organic material decomposes in the soil. Standard tea bags were buried and left to decompose across 9,000 locations, and after three months they were recovered and the tea was weighed. The final celebration of the Science Year was an event at the Museum für Naturkunde – Leibniz Institute for Evolution and Biodiversity Science (Museum of Natural History) in November 2021 during the exhibition NaturFutur – Bioökonomie erleben (Future of Nature – Exploring the Bioeconomy), a cooperation project between the information platform bioökonomie.de and the Museum für Naturkunde – Leibniz Institute for Evolution and Biodiversity Science.

Interfaces for social dialogue

Bioeconomy Council: The third Bioeconomy Council was appointed at the end of 2020 and advises the German government on the implementation of the National Bioeconomy Strategy through recommendations, statements and expert reports. Another responsibility is the promotion of public debate on the bioeconomy. The Bioeconomy Council is set to involve civil society in the debate on conflicts arising during the implementation of the sustainability goals of the bioeconomy, and to draft suggestions and recommendations for a roadmap for the National Bioeconomy Strategy through a participatory process. One way of approaching this are focus groups with the involvement of stakeholders in order to intensify open discourse between the public, science and politics, as well as an annual Bioeconomy Forum.

Dialogue platform Industrial Bioeconomy: This think tank was launched by the Federal Ministry of Economics in 2018 to foster exchange between industry representatives on the one hand and science and civil society on the other. Stakeholders from industry, associations, science, trade unions as well as Federal State and German Federal Ministries are represented. The members of the platform give recommendations on how to better enable public dialogue. Best practice examples and model regions are seen as a key tool.

Bioeconomy careers

The bioeconomy covers all economic sectors and numerous scientific disciplines. This will require specialists with interdisciplinary expertise at the interfaces between sustainability, production processes, markets and consumption. While the next generation of scientists is being trained at universities and non-university research institutions, the bio-based economy also offers a wide range of prospects for people with innovative business ideas who are willing to start up a business.

Linking different industries, fields and areas of expertise under the umbrella of the bioeconomy creates new opportunities, but also new requirements in terms of professional qualifications. They are a prerequisite for innovation and growth and will make an essential contribution to the sustainable bioeconomy in Germany. Experts with broad specialist knowledge and interdisciplinary qualifications are needed.

Bioeconomy research landscape

Universities and non-university institutions across Germany act as bioeconomy research hubs. According to a research survey from 2021 conducted by the information platform biooekonomie.de, more than 800 institutes and research facilities perform research in this field. Over 70 universities and 64 universities of applied sciences are active in bioeconomy research, as are more than 156 non-university institutes of the Fraunhofer-Gesellschaft, the Max Planck Society, the Leibniz Association and the Helmholtz Association as well as around 40 departmental research institutions *(see chart p. 6)*. As the survey shows, the bioeconomy encompasses many different subjects. Of the 357 respondents, most conduct research in the areas of agricultural science, biodiversity research, biotechnology, process engineering and environmental technologies *(see chart p. 85)*. What's more, research efforts are also underway in social sciences, economics and political science.

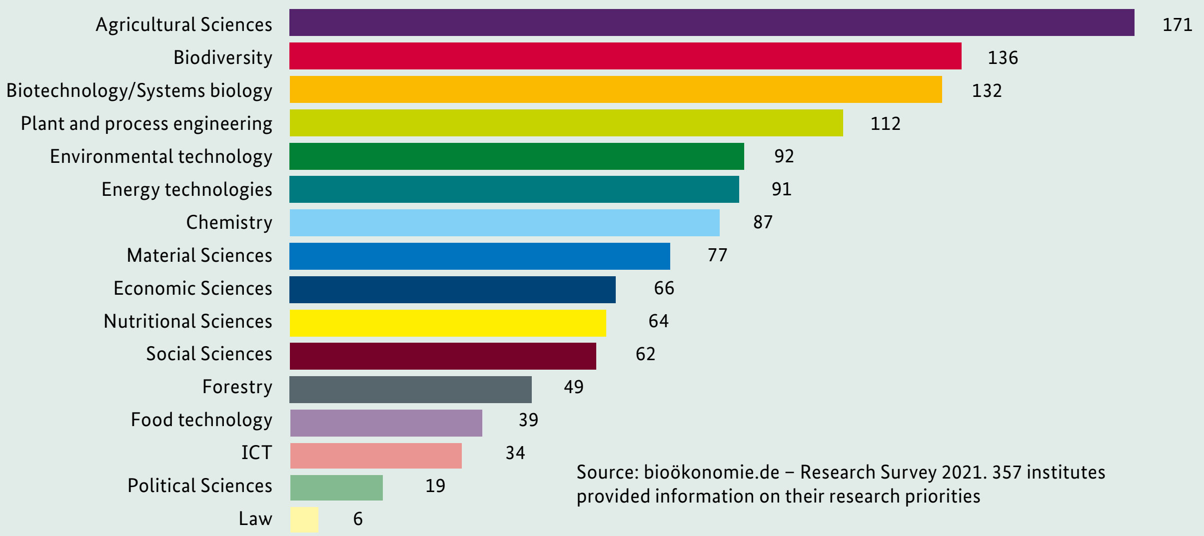
The German Federal Government's research funding has promoted the development of knowledge and interdisciplinary networking in science. Since 2010, over 2,000 research projects have been funded under the National Bioeconomy Research Strategy. This has provided many young scientists with valuable qualifications for careers in academia or business. Several thousand Bachelor's and Master's theses have been produced as part of the funded projects.

The Federal Government is building on this and has identified the qualification and training of specialists as one of the overarching instruments for implementing the National Bioeconomy Strategy.

Junior research groups for sustainable bioeconomy research

A particularly attractive form of qualification is the funding of junior research groups through a range of initiatives, such as the Biotechnology 2020+ Research Award. The award winners received funding for five years for their own research group with which

Core areas of the institutes with bioeconomy research in Germany



Source: bioökonomie.de – Research Survey 2021. 357 institutes provided information on their research priorities they can continue to work on new biotechnological production processes. Projects funded through the Research Awards cover many fields ranging from bioelectrotechnology for the production of basic and fine chemicals (Falk Harnisch), to cyanobacteria as hydrogen factories (Kirstin Gutekunst), to designer organelles as artificial reaction spaces in cells (Stefan Schiller).

Through the initiative Bioeconomy as Societal Change, the BMBF is funding junior research groups investigating relevant aspects from politics, social sciences and economics. The researchers address a wide range of topics – from the circular economy in the bioeconomy, to the analysis of innovation processes in bioclusters, social inequalities in the bioenergy or food sectors, and societal change around the globe.

The BMEL also supports junior research groups as part of its funding activities. These work on different topics ranging from innovative wood-based building materials to new oleochemicals and new approaches to processing bioplastics, to process management optimisation in biogas plants.

Job prospects for bioeconomy students

In addition to an international Master's degree programme in Bioeconomy, the University of Hohenheim offers several other degree programmes related to the bioeconomy, such as Biobased Products and Bioenergy, Food Science and Biotechnology and Agricultural Biology. During an interview with biooekonomie.de, Iris Lewandowski, Chief Scientific Officer at the University of Hohenheim and Co-Chair of the Bioeconomy Council, said:

"Our degree programmes are of particular interest to students who want to be involved in shaping a sustainable future. The responsibilities here are as varied as the profiles and jobs that our graduates end up with. Many are hired by corporate sustainability departments, others are hired to manage projects or develop bio-based products. Some graduates join national or international research institutes and institutions, while others found their own start-ups."

The BMBF concept Nachwuchsförderung für eine nachhaltige Bioökonomie (Concept for the Promotion of Young Scientists for a Sustainable Bioeconomy) published in 2021 is rooted in the Sustainability Agenda which is part of the National Bioeconomy Strategy. This creates a direct link between sustainability and the funding of young researchers in the bioeconomy.

The funding initiative Kreativer Nachwuchs forscht für die Bioökonomie (Creative Young Researchers for the Bioeconomy) was launched in 2021 and is aimed at scientists from the natural sciences, information technology and engineering at universities, other research institutions and businesses. The approaches for the implementation of the bioeconomy promoted as part of the project must be based on, and build on the objectives of the United Nations Sustainable Development Goals (SDGs).

Junior research groups are eligible for funding for a period of up to five years to enable them to work in an interdisciplinary manner, building bridges between the social, natural and technical sciences. The funding initiative will make several calls for proposals every year and tries to encourage the return of young German researchers who have been working abroad and to attract young foreign scientists to come to Germany. Thanks to this funding, the initiative is able to offer attractive career opportunities within the German research community. In order to create the best possible conditions for young researchers during a crucial phase in their careers, the measures for promoting young researchers include support from mentors, including international mentors. After successful completion of the projects, the junior research groups are to go on to form an alumni network.

Studying bioeconomy

The range of possible training opportunities for working in the bioeconomy is just as diverse as the research activities in the field. Vocational and technical colleges, universities of applied sciences and universities all offer a way into the bioeconomy. One standard way is an academic degree in agricultural science, biotechnology, chemistry, food technology, economics or social sciences. In addition, more and more universities and universities of applied sciences are setting up specialised bioeconomy courses and degrees. In Germany, TUM in Munich (B.Sc. Bioeconomy) and the University of Hohenheim (M.Sc. Bioeconomy) offer interdisciplinary degrees in bioeconomy, and a Master's programme in Bioeconomy is currently being established at the University of Greifswald. In addition, there is a wide range of programmes across Germany covering sustainability, resource management and socioeconomics. According to experts, bioeconomy training should be both multi- and transdisciplinary as well as practice-oriented. It should also foster integration and cooperation skills and the ability to think systemically. Digital technologies and applications are also becoming increasingly important.

Launching a business with innovative ideas

Scientific research often inspires good ideas. Turning an idea into a marketable product, however, is often a long and costly process. So how can an idea be turned into a business? Experience has shown that putting a bio-based economy into practice requires some exceptional ideas and novel funding instruments.

This is why the ideas competition New Products for the Bioeconomy is aimed primarily at young scientists at universities and non-university research institutions. The aim is to offer people with unique product ideas for a bio-based economy easy access to funding. The first step is an exploratory phase during which a new idea for a bio-based product or process can be refined. This is followed by a two-year feasibility assessment phase. Other funding formats, such as GO-Bio or EXIST, also offer interesting early-stage funding opportunities for research teams looking to launch their own bioeconomy innovations.

University projects during the Science Year

Young researchers contributed to bioeconomy activities during the Science Year 2020/21 in a variety of ways. A total of 25 projects by young researchers were awarded 10,000 euros each as part of the Wissenschaft im Dialog (Science in Dialogue, WiD) competition for their communication ideas on the topic of the bioeconomy, with students, doctoral candidates and postdocs participating.

The digital Bioökonomie-Camp (Bioeconomy Camp) in autumn 2021 was the research convention of the Science Year, organised by the BMBF and the University of Hohenheim. The programme consisted of interactive panel discussions, barcamp sessions, deep-dive workshops and roundtable discussions and was able to show how important inter- and transdisciplinary work is for the bioeconomy.

At European level, the European Circular Bioeconomy Fund (ECBF) provides access to venture capital. The EU initiative has already raised more than 300 million euros and invests in German companies, among others.

Further links

Federal Ministry of Education and Research (BMBF)
More information on the National Bioeconomy Strategy and the BMBF's bioeconomy funding can be found on these websites.
bmbf.de/biooekonomie
fona.de

Federal Ministry of Food and Agriculture (BMEL)
This website provides an overview of the BMEL's bioeconomy funding.
bmel.de/DE/themen/landwirtschaft/bioeokonomie-nachwachsende-rohstoffe/ueberblick-biooekonomie.html

Federal Ministry for Economic Affairs and Climate Action (BMWK)
On this website, the BMWK presents, among other things, the Förderprogramm Industrielle Bioökonomie (Industrial Bioeconomy Funding Programme).
bmwi.de/Redaktion/DE/Dossier/industrielle-biooekonomie-wachstum-und-innovation.html

Bioeconomy Council
The website of the German Federal Government's advisory body on the bioeconomy.
biooekonomierat.de

Information portal biooekonomie.de
The information portal on the bioeconomy in Germany and worldwide provides news, portraits, interviews and in-depth reports, videos and podcasts, multimedia stories as well as databases on funding projects and research institutions.
biooekonomie.de is an initiative of the BMBF.
biooekonomie.de

Informationsportal pflanzenforschung.de
News and background information on various aspects of plant research.
The online portal is funded by the BMBF.
pflanzenforschung.de

wissenschaftsjahr.de
The Science Years are a science communication initiative by the BMBF, with 2020/21 being dedicated to the bioeconomy. The official website provides news, background information and information on activities to join in. **wissenschaftsjahr.de/2020-21**

Projektträger Jülich (Project Management Organisation Jülich)
Many bioeconomy projects are organised by Jülich on behalf of the German Federal Ministry of Education and Research. **ptj.de/fokusthemen/biooekonomie**

Fachagentur Nachwachsende Rohstoffe (Agency for Renewable Resources, FNR)
The Fachagentur Nachwachsende Rohstoffe (Agency for Renewable Resources, FNR) is the project management agency of the Federal Ministry of Food and Agriculture (BMEL) **fnr.de**

Renewable product world
FNR product and supplier catalogue that presents the diverse range of products from renewable raw materials available to public sector procurement officers and consumers.
die-nachwachsende-produktwelt.de

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