Circular Bioeconomy for Germany

A roadmap by the Fraunhofer-Gesellschaft for implementing the bioeconomy in Germany

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Management Summary

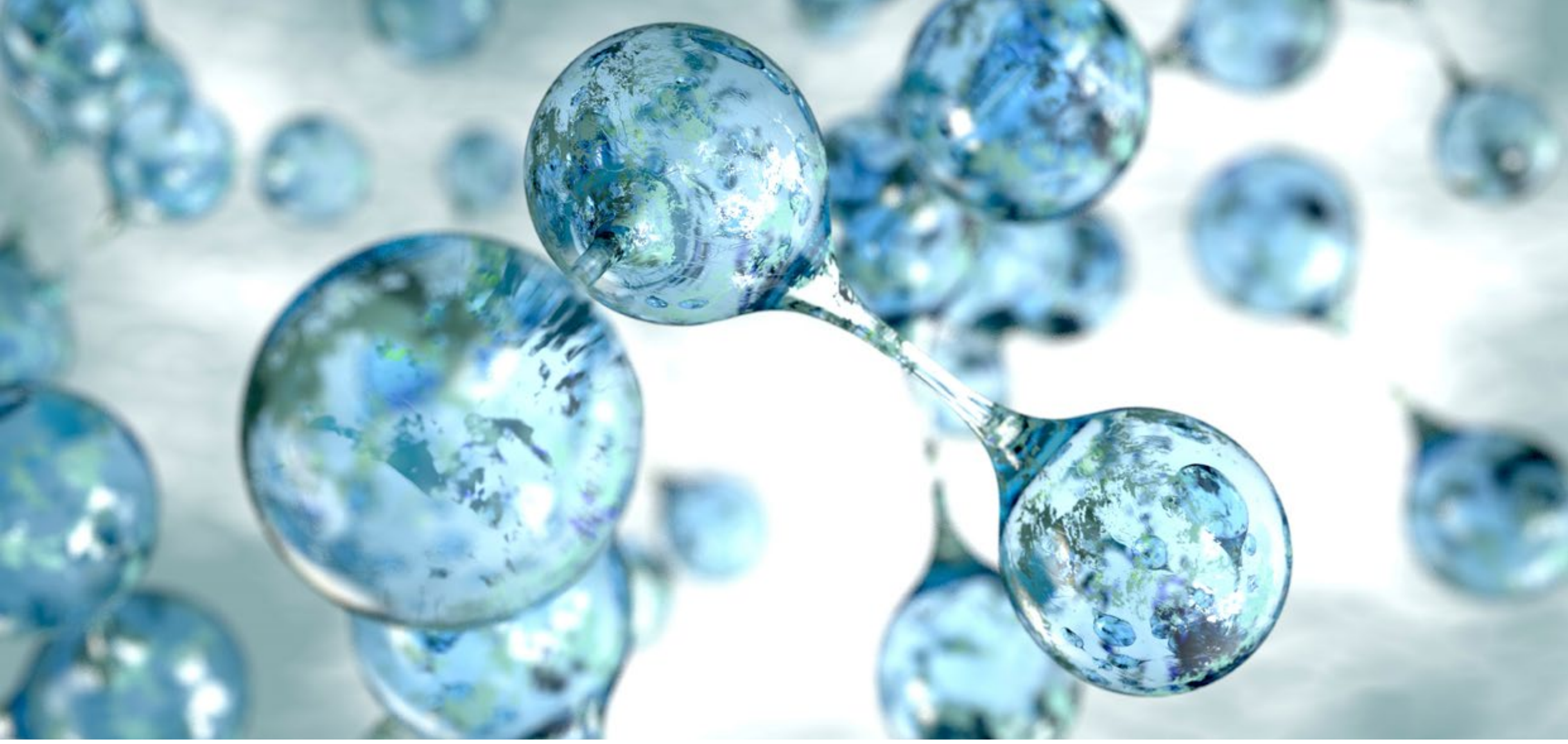
How can we successfully implement a circular bioeconomy? And what activities will this involve? This roadmap explores these questions in detail from a scientific and technical perspective. Convincing society altogether about the essential need to establish a sustainable economic system, thereby ensuring our social, economic and environmental well-being, is clearly a matter of overarching importance - moreover, it is evident that this must happen soon. In our current political and economic climate, the willingness of society as a whole to accept and help shape change has increased significantly. The multitude of global crises and the resulting shortage of raw materials make it very clear to all of us that the resources that have been available in sufficient quantities up to now will soon be limited or may not even be accessible in the future. The access to many raw materials depends heavily on other countries' resources. Geopolitical events have increased the focus on the issue of Germany's sovereignty as an industry location in social and political spheres. This situation calls for short-, medium- and long-term solutions to reduce Germany's raw material dependencies. At the same time, these solutions also present an opportunity to minimize the continuous progression of climate change as much as possible.

In this context, it is of utmost importance to shift away from using fossil raw materials and adopt a more sustainable economic system. This is the reason why more and more countries and regions around the world are developing bioeconomy strategies to lay the conceptual basis for societal change. In addition, the industry sector is becoming increasingly open to the transformation from its current, primarily linear system to a circular, sustainable economy. The bioeconomy can also add momentum here.

Successfully implementing a sustainable, circular bioeconomy requires profound societal change. This must go hand in hand with rethinking the way we produce and use biogenic raw materials and tap into alternative raw material sources, such as carbon dioxide (CO_2). This roadmap outlines a range of strategies that can help produce a successful transformation, including the following:

- Improving process efficiency, cascade use and increase recycling by intensifying value creation of biogenic waste and residues from agriculture and forestry, industrial production and private households
- Tapping and utilizing CO_2 as carbon source
- Transferring available technologies for utilizing biogenic raw materials and manufacturing sustainable products into market settings, considering the entire system, from logistics and supply chains to site-specific factors
- Knowledge-based improvement in the production and quality of cultivated biomass through biotechnology and breeding research
- Supplementing biomass production on farmland, e.g., through indoor farming, and expanding biomass production by harnessing marginal land
- Increasing the ecological, technical and social resilience of systems for cultivating, producing and utilizing biomass in line with environmental, climate and biodiversity protection targets
- Involvement of all relevant stakeholders and the public as early as possible with a focus on opportunities in such a way as to increase acceptance at the industrial and societal level, which is a key factor for the success of a transformation process

Building on these approaches, this roadmap presents specific options for sustainably harnessing biomass and other carbon sources and their utilization in a resource-efficient manner in the fields of food and material use, and gives precise suggestions for a successful realization of the transformation toward a sustainable economic system. Moreover, it offers recommendations for action for political decision-makers to implement new, innovative processes that benefit the economy, society and the environment alike.



Introduction

Our society is currently facing an array of major challenges. They range from climate change and worldwide resource shortages through the continuous growth of the world's population and its increasing consumption requirements, right up to international conflicts along with the impact they have on global supply chains. Devising adequate solutions for countering these challenges requires collaborative efforts by industry, research, politics and society. Profound activities are called for here, to enable our society's much needed transformation toward a sustainable mode of production and our way of life. At the same time, an effective turnaround is needed in the agricultural, energy, resources and intermediate goods sectors. Achieving these goals will require innovative technological solutions, economically attractive incentives for industry and social acceptance of new ways of living. We need to ensure that these actions are environmentally sound to protect and support the regeneration of our ecosystems and biodiversity. Being one of the world's leading applied research organizations, the Fraunhofer-Gesellschaft sees the bioeconomy as a central element of this transformation. If we consistently implement the bioeconomy within our daily lives, we will have a chance to allow future generations to continue living healthy, safe and dignified lives.

Bioeconomy is defined as the production, exploitation and use of biological resources, processes and systems (including information and knowledge) to provide products, processes and services in all economic sectors within the framework of a sustainable economic system [1]. New bioeconomy products and technologies have the potential to secure jobs for the future, bolster standards of living, contribute to global food security and help protect the climate and the environment. The bioeconomy must be developed in such a way as to respect planetary boundaries and give equal weight to each of the three pillars of sustainability - the environmental, economic and social perspectives. Assuming that these conditions are respected, the bioeconomy will play an important role in achieving the UN's Sustainable Development Goals (SDGs) and the targets set out in the Paris Agreement [2, 3]. Bioeconomy represents an opportunity to combine forces across different sectors and scientific disciplines by means of a systemic approach that encompasses the entire society. In this context, essential elements for a successful transformation include testing out and introducing new products and technologies, including a variety of stakeholders in decision-making processes, and engaging them in a constructive public debate on possible conflicting objectives.

Guiding principle: circular bioeconomy

As an applied research institution, the Fraunhofer-Gesellschaft is leveraging its bioeconomy expertise in order to make a decisive contribution to the transformation toward a sustainable, resource-efficient world. In its research activities, it is guided by the principle of a circular bioeconomy, a synergy of the concepts of the bioeconomy and the circular economy [4]. All Fraunhofer institutes active in the bioeconomy field share one common mission: to develop biotechnology, process engineering, digital, circular and systemic solutions that enable us to use natural resources responsibly and to bring these solutions into practice in industry. As an expert partner for industry companies, the Fraunhofer-Gesellschaft focuses on strengthening Germany's position as an industry hub. At the same time, however, the organization understands that it has an equal responsibility to make vital contributions to overcoming major challenges that affect society as a whole.

The challenges facing the world urgently require a shift from a linear, resource-intensive and emissions-intensive economic model to a circular economy based on value-added cycles and networks, which largely eliminates the use of fossil resources. Due to climate change and diminishing petroleum, natural gas and coal resources, we have no choice but to make a full transition from using fossil-based carbon to alternative, sustainable raw material sources.

The circular bioeconomy is centered on developing and implementing innovative processes and products and on developing new business models and value creation networks, which in sum focus on circular utilization of raw materials in production processes, taking into account economic, environmental and social factors.

A circular bioeconomy of this nature would be largely based on biogenic raw materials from the agricultural and forestry sectors, along with residues, wastewater and carbon dioxide (CO_2), which would be utilized in multilevel, cascading cycles and recycled to the greatest extent possible (fig. 1). In this context, "cascading use" is defined as repeated utilization of material with possibly decreasing added value as well as a final energy recovery or composting of the residues. In addition, biotechnological processes and biology know-how can be harnessed to support recirculation and cascading use of abiotic raw materials, for example, by recovering metals for industry applications or inorganic materials for producing fertilizers. The goal is to continuously improve resource utilization, make it more environmentally compatible and reduce greenhouse gas emissions, and to create value from secondary material flows and residual flows.

Production processes that use non-fossil raw materials in combination with a circular economy model are a necessary starting point for the circular bioeconomy; however, they do not automatically lead to a sustainable economic system. Suitable economic, political and social conditions must also be created so that scarce cultivation space and raw material flows are utilized as efficiently and productively as possible. Unavoidable conflicts in goals and utilization purposes must be objectively identified in advance through scenario analyses and foresight processes in order to find prospective, preventive and proactive solutions in opportunity-oriented dialog processes with all relevant stakeholders.

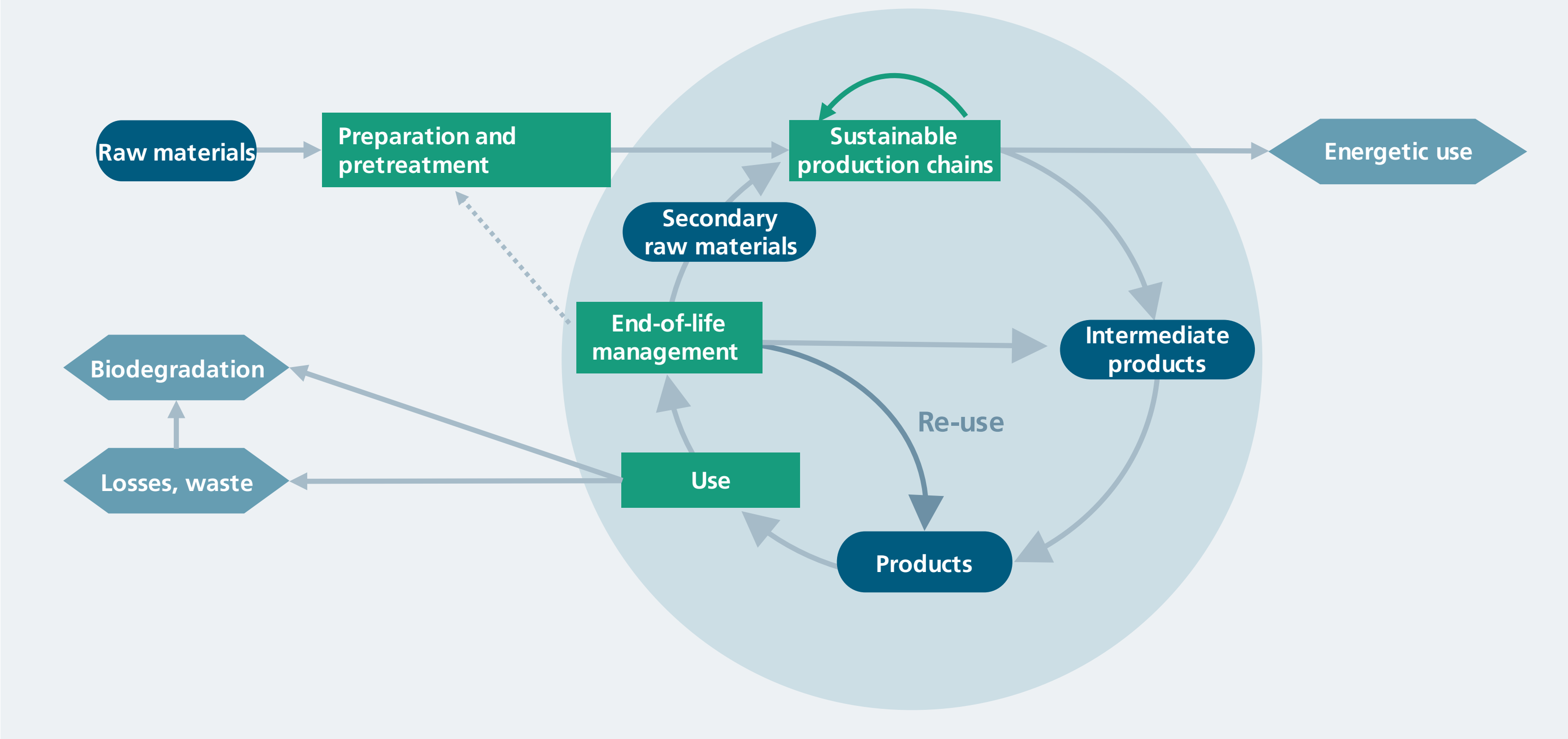


Fig. 1 Concept of the circular bioeconomy and its elements

Status quo and challenges

The enormous potential of the bioeconomy and the pressing need for the transformation have already been acknowledged around the world. More than 50 countries have adopted individual bioeconomy strategies and started to make progress toward their goals [1]. To focus the bioeconomy beyond the activities of individual European countries, the European Commission published the first European bioeconomy strategy in 2012, which has since undergone continuous revision [5–7]. The bioeconomy boom is also making its presence felt at the individual state level in Germany, as various states and regions have developed their own bioeconomy strategies or are currently in the process of developing them [8–11]. In addition, the federal government and the states have put a variety of programs and initiatives in place in order to expand the bioeconomy in Germany.

The German federal government has also laid down guidelines and targets for a national bioeconomy policy and implementation measures that apply across all states; starting with the Cologne Paper, which was developed at EU level, and continuing with the National Research Strategy BioEconomy 2030 [12, 13]. The current National Bioeconomy Strategy aims to safeguard the German industry sector's competitiveness and sovereignty and increase its resilience [1]. Biology know-how and a comprehensive understanding of interconnected relationships within ecosystems are facilitating the establishment of new products and processes. At the same time, the renewal of traditional forms of enterprise and the establishment and restructuring of value chains in an ecologically and socially compatible manner are being driven forward. The Fraunhofer-Gesellschaft views itself as committed to these goals, and with this roadmap, it aims to lay out possible courses of action from a scientific and technical perspective that contribute to achieving these goals.

The following sections outline relevant, necessary developments in terms of the availability and demand for biomass, describe the factors that influence the possibility of implementing the technologies and formulate the key basic premises for the roadmap. Along with the transformation goals summarized above, these basic premises provide advice and recommendations on how policymakers can make a decisive contribution to the implementation of the bioeconomy, including by supporting the research sector and setting guidelines. The roadmap also indicates the topics and key focus areas which should be addressed from the perspective of application-oriented research in order to achieve this goal.

Biomass as the key raw material for the bioeconomy

At present, biomass is the key raw material for the bioeconomy. Assumptions regarding the future availability of biogenic raw materials are an essential factor for estimating demand for technologies and innovations and assessing their potential. Utilization conflicts must be anticipated and avoided, even in highly vulnerable conditions. Scarce raw materials must be utilized in such a way as to achieve climate protection (strengthening and maintaining biodiversity) and sustainability goals to an equal extent.

Currently, the primary sources for biomass are the agricultural and forestry sectors. Traditionally, these sectors have supplied foodstuffs, renewable biogenic materials and energy carriers. Due to many different factors, such as the growing world population, increasing prosperity and the associated global rise in demand for foodstuffs and consumer goods, higher demand for these raw materials is also expected in the future. The ongoing implementation of the bioeconomy is further increasing the demand for biomass. As a consequence, more land may be used for biomass production, possibly resulting in a land use conflict regarding e. g. food and feed production. At the same time, the agricultural and forestry sectors' capacity to provide biomass is under threat, as climate change is contributing to the deterioration of soil quality and fertility, and even desertification and marginalization of land in many regions of the world. Extreme events such as droughts and floods are increasing in frequency, duration and intensity. The viability of entire ecosystems, such as paludal and permafrost regions, is being impaired, and their resilience is being weakened. The dramatic loss of biodiversity is both a cause and a consequence of these global changes. However, intact, viable ecosystems are essential for productivity and sustainability in the agricultural and forestry sectors. For many years, there has been intensive discussion about the extent to which the provision of biomass can be sustainable, especially on agricultural land.[1] According to estimates by the International Institute for Sustainability Analysis and Strategy (IINAS GmbH), the potential for sustainably producing biomass excluding residues from agriculture (by 2050) is significantly lower than the volumes produced currently [14].[2] In addition, there is hardly any potential for covering the demand for sustainably produced biomass through global trade. The latter is only functioning to a limited extent even within the EU, and the environmental consequences of domestic biomass demand for other nations are viewed very critically [15].

Furthermore, even within agricultural and forestry production of biomass, land use and utilization purpose conflicts are arising between ecosystem services[3], food and feed production and the use of the available biomass as a raw material and an energy source. In both this paper and the National Bioeconomy Strategy, food security is defined as the primary objective, ahead of the material use and energy use of biomass [1].

Biomass supply, demand and the associated challenges

In order to give an overview of the availability and utilization of biomass, it is necessary to consider land availability, domestic biomass production, importing and exporting of biogenic raw materials and products that can be processed further. While the most up-to-date figures in these areas only come from 2015, more recent reports on subsectors support the conclusion that no fundamental changes have occurred since that time [14].[4] Germany's domestic biomass production volume comes to around 185 million tons (fig. 2). A large portion of this biomass (including the imports) stems from agricultural production. Even today, Germany imports more biomass and biomass-based products than it produces, meaning that it shifts a major share of the environmental effects associated with intensive land use to other countries. This can lead to social and political imbalances and, as such, must be taken into account during the preliminary stages of any future efforts to develop processes for utilizing biogenic raw materials.

In Germany, the greater portion of this biomass is currently used for feed. The second largest portion goes to the production of bioenergy, with material use only coming in at third place (e.g., wood for furniture and paper). Direct production of foodstuffs for human consumption takes up the smallest volume (approx. 10 percent) [16].

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[1] In sustainable biomass production, care is taken to ensure that the land used for cultivation can regenerate and will thus also be available for future generations. In this way, sustainability covers economic and social issues as well as the environment.

[2] The potential volume of sustainably produced biomass that can be obtained from agriculture (excluding residues) amounts to 77 million tons in dry weight, while the volume currently produced amounts to 140 million tons in dry weight [14].

[3] Ecosystem services: Direct or indirect contributions from ecosystems to human wellbeing.

[4] More up-to-date estimates regarding biomass utilization refer to the figures mentioned here or come to similar conclusions (e.g., [14]). In addition, the surface area used for agriculture has only decreased slightly in recent years and forestry area has also remained constant. Data on harvest volumes for grains, for example, does not show any clear trend, even when yearly fluctuations are taken into account.

Material flow of the bioeconomy in Germany

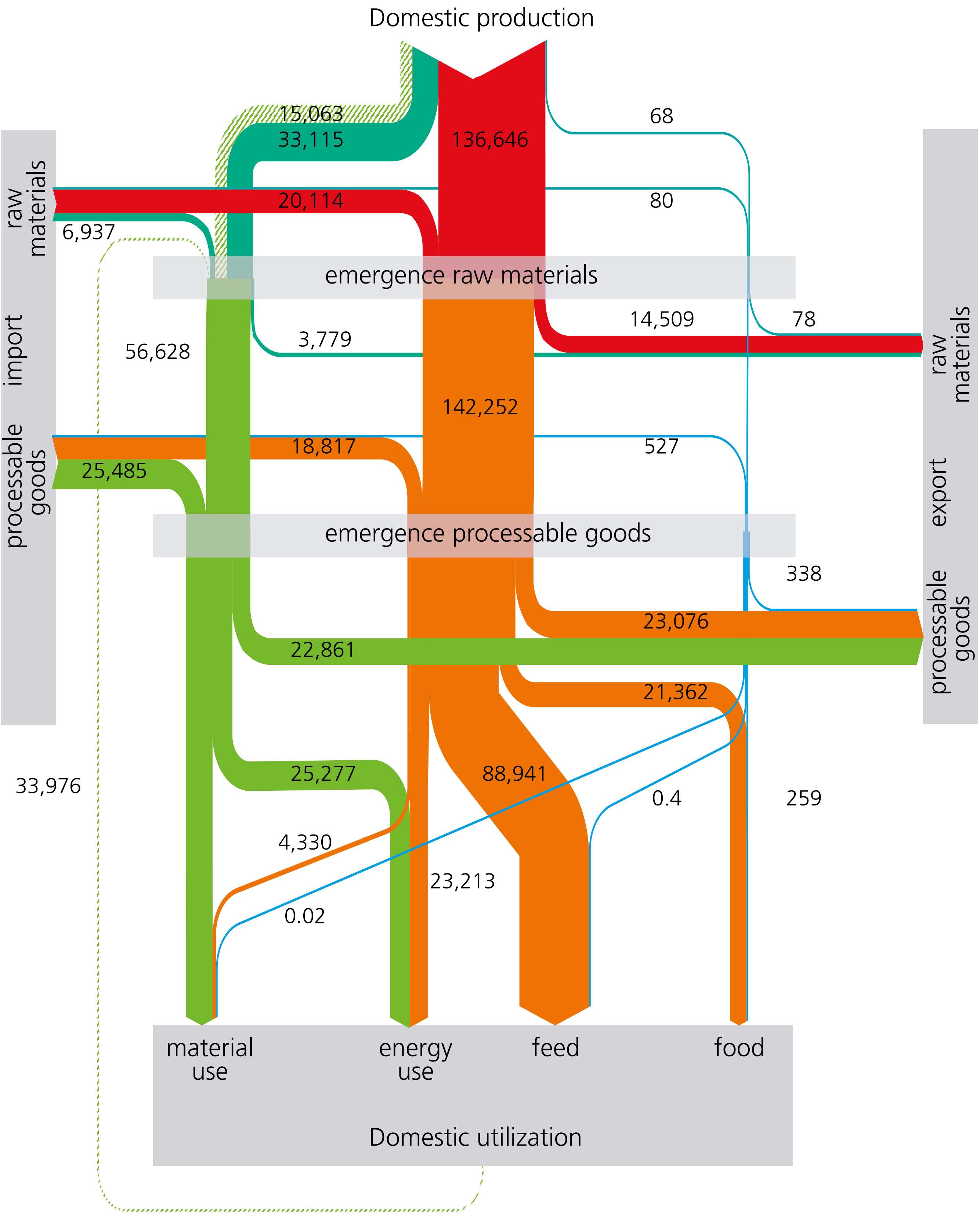

Fig. 2 Biomass flows in the German bioeconomy (in 1,000 t dry matter) (2015). Green: forestry, orange: agricultural, blue: aquatic. Source: Thünen Institute [16]

For many industry sectors, biomass is one of the few available alternatives to fossil raw materials. As such, it has been assumed for quite some time that the use of biomass as a raw material will play an important role in sustainable industrial development. Renewable biogenic raw materials have already found their way into many markets in recent years, cropping up in a wide range of products, from construction materials, paper and cardboard to rubber goods and intermediate products for the chemical industry. Not only the chemical industry, but also the textile, construction, pharmaceutical and cosmetic industries are using large quantities of biomass for material utilization. In the future, significant growth rates are also expected in various markets, such as bio-based lubricants and surfactants [17]. However, due to the limited availability of biomass, it appears that only utilization pathways characterized by high levels of raw material efficiency and low levels of conflict with food and feed production are viable options for the future. Therefore a sustainable bioeconomy is characterized by an efficient production, processing and use, taking environmental and ethical factors into account.

The use of biomass as an energy source is authoritatively governed by statutory regulations, particularly the EU Renewable Energy Directive and the legislation for implementing it at a national level [18]. Due to projected biomass scarcity, many experts are calling for reduction in the use of biomass as an energy source and for the repurposing of that biomass in other areas [14]. This in turn gives rise to a need to increase cascading use and to recycle the majority of waste and residues for, among other things, energy conversion and fuel production [19]. As such, biomass for energy use should therefore be limited to material streams that can serve neither food nor material use. In this context, it is important to emphasize that material and energy use of biomass are not mutually exclusive. Knowledge-based breeding adaptation of plants to suit the final material's relevant area of use will play an essential role here. For example, plant properties that made a specific crop unsuitable for use as food or feed could present an advantage in technical applications, while simultaneously increasing ecosystem resilience and supporting biodiversity. Consequently, rather than dwelling on perceived oppositions and conflicts, we need to highlight systemic connections and synergies, and look for advantages for industry, the environment, the socio-economic situation and, where relevant, even the political sphere, e.g., safeguarding the sovereignty and resilience of the German nation.

Alternative raw materials for the bioeconomy

Biogenic residues and waste are playing an increasingly important role in overall industrial use - for material or energy use. The advantage of these feedstocks is that they do not compete with food and feed production. Using waste in this way would result in fewer detrimental effects on ecosystem stability and the security of human food supply than the use of wood from the forestry sector or agricultural biomass [20]. Studies have demonstrated that, as of 2015, the technical potential in the area of biogenic residues, byproducts and waste in Germany falls within a range of 85.6 to 139.6 million tons of dry matter [21]. Between 66 and 84 percent of this volume is already being used.[1] As such, a technical potential of around 14 to 48 million tons of dry matter remains to be exploited.[2] This corresponds to roughly 7 to 22 percent of current biomass utilization volumes. Consequently, biogenic residues and waste materials constitute a significant potential biomass source for a variety of purposes and could help create a considerable amount of value for the circular bioeconomy.

In addition to the utilization of biogenic residues and waste, another important possible means of reducing land requirements involves using other raw materials apart from biomass as an energy and material source. Carbon capture and utilization (CCU) uses CO_2 as a raw material for manufacturing hydrocarbons [22, 23]. CCU technology enables extensive technical carbon cycling, along with the detachment of fossil carbon sources (such as natural gas and crude oil) as well as renewable raw materials. It should be noted that although CCU processes are already technically feasible, they are not yet economically viable for the most part due to their high energy consumption levels. In many CCU processes, it is essential to simultaneously provide hydrogen to react with the CO_2; for sustainability purposes, this should be produced via electrolysis processes powered by renewable energy. The hydrocarbon compounds produced in this way (such as methanol) can serve as basic materials for the chemical and plastics industries, and as fuels for the transportation sector. Sectors such as the chemical industry could switch to using this method as a raw material source via various process routes [24]. Many research and development initiatives have already made such significant progress in this area that even today, low-molecular chemical basic components are being manufactured from hydrogen and CO_2 via Power-to-X (PtX) processes. In the future, in order to produce more complex organic molecules, it will also be necessary to consider biotechnological processes for converting CO_2.

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[1] Material use accounts for the largest share (54 to 58 percent). Energy use accounts for 37 percent and about 5 to 9 percent cannot be clearly assigned to material or energy use [20].

[2] The figures are given as a range due to uncertainties in the elements used for calculation. The literature reviewed by the working group contained very wide ranges regarding wet and dry matter content and recovery rates for residual forest wood.

Possible CO_2 sources include carbon sequestration, for example, at emission point sources (e.g., in steel and cement works, power plants, and waste incineration and waste water treatment facilities) or directly from the air (known as direct air capture (DAC)). In this context, it should be noted that the German Climate Action Plan has stipulated that the industry sector should reduce its emissions from 172 million tons of CO_2 equivalent (as of 2020) to 118 million tons of CO_2 equivalent by 2030 [25].

It is important to be conscious of the fact that, apart from a few exceptional cases where CO_2 emissions cannot be avoided (e.g., the cement industry), obtaining carbon from point sources is only an interim solution, because the goal in general is to avoid CO_2 emissions completely. However, CCU processes can improve the carbon footprints of the current generation of industry plants, while simultaneously making the processes more fit for practical application and scaling them up.

The framework conditions described in this chapter, i.e., the availability of biomass and other non-fossil carbon sources, form the basis for the successful implementation of a circular bioeconomy that meets economic, environmental and social requirements. The next chapter will elucidate the research and development (R&D) requirements arising from these assumptions and the challenges described here, along with proposing some possible solutions.

Applications and opportunities for the bioeconomy

In this chapter, some important value chains of the bioeconomy are illustrated on the basis of the following use cases: "Food" and "Material use of biomass and CO_2". The current state of the respective technologies is described and an outline is given for the R&D requirements in the respective sectors. The chapter also discusses obstacles to be faced in applied research and in transferring research to application.

Food

The challenges described above have clearly shown how volatile and fragile production and supply chains can be, even if they have been established for decades. This is why prices for many food staples have increased significantly over the last 20 years [26]. For example, the price of rice has grown more than 2.5-fold from 2003 to 2023 [27]. As a result of this global trend, the number of people suffering from hunger world-wide has started to increase again for the first time since World War II, as shown in a study by the Food and Agriculture Organization of the United Nations (FAO). This study assumes that even before the start of the war in Ukraine, around 800 million people worldwide could not satisfy their daily calorie requirements [28].

Consequently, providing a resilient supply of safe, high-quality food for a continuously growing world population constitutes one of the greatest challenges of the 21st century. Although our current agricultural production levels can provide sufficient plant-based food for 9.5 billion people in 2050 [29], producing an adequate number of calories is not enough for a healthy diet. Even now, a lack of micronutrients and, in particular, an insufficient supply of high-quality protein are the primary causes of what is known as "hidden hunger", a phenomenon that occurs in large areas of the world [30]. Every year, it is the cause of death for around 700,000 children under the age of five worldwide [31]. The shortage of protein is expected to worsen due to soil degradation and extreme weather events caused by climate change [32, 33]. While malnutrition and undernourishment are growing worldwide problems, the number of people suffering from excess weight and obesity is also on the rise [34]. In Germany, the population's eating habits only correspond to the recommendations of the German Nutrition Society (DGE) to a limited extent. This malnutrition is partially responsible for the rise in obesity, cardiovascular disease, diabetes mellitus and many forms of cancer. One in five deaths in Germany and 30 percent of the healthcare system costs are associated with poor dietary habits and could be avoided in the majority of cases [35]. Unless targeted measures are adopted, it is to be expected that Germany will not see any improvements in dietary habits or the incidence of related diseases [36].

Decades of dietary research have proven that current approaches do not lead the population to adopt a consistently healthy lifestyle. A lasting change to dietary and lifestyle habits would require newer, more holistic communication strategies and targeted inclusion of all the necessary stakeholders from science, industry, politics and civil society. Possible solutions include AI-based apps for personalized dietary advice and innovative food products that combine excellent sensory properties with a high nutritional-physiological profile.

When the entire value chain is considered, around a third of the foodstuffs produced worldwide end up in secondary or waste material flows [37]. Some of these secondary material flows consist of inedible components of the food products and are consequently unavoidable. However, these flows could potentially create value through cascading use as a source of materials and energy.

In light to the situation described above, the following have been identified as priority areas where action is required:

1. Increasing technical resilience along the food value chain
2. Global food security
3. Central focus on sustainable, healthy food for the well-being and health of individuals
4. Reduction of avoidable food waste and utilization of unavoidable food waste and secondary material flows

Resilience of food value chains

Increasing the resilience of supply chains

The food industry is characterized by highly interconnected value chains, on both a local and global level. The coronavirus pandemic, among other things, has demonstrated that the ability to remain resilient against all types of disruptions can be a key competitive advantage. In the food industry, the "resilience" of value chains refers to their ability to maintain supply chains despite disruptions in production and processing and, above all, to always guarantee consumer safety. To assess the resilience of the food industry, we must consider the complex factors affecting supply chains and, most importantly, production processes.

Resilience can be increased by planning strategies and countermeasures that enable the system as a whole to rapidly return to its original or target state. As such, "resilience" refers to the ability to maintain stability despite internal and external influences and disruptions. By ruling out external influences through methods such as indoor farming, disruptions from the outside can be largely eliminated and residual risks can be targeted and reduced, significantly improving the resilience of the system. Among other things, it is necessary here to weigh up possible expenses (e.g., the energy consumption required for indoor cultivation) against other processes of consumption (e.g., additional expenses for packaging and transportation), and to take into account the higher quality of regional provision from such cultivation systems. This way, innovative cultivation strategies for regional or urban settings can reduce the need for storage facilities in distribution, trade and logistics chains. When coupled with sustainable, regional energy supply plans, these strategies also serve to strengthen the resilience and sovereignty of the energy supply.

In order to increase the resilience of complex technical systems such as food processing plants, it is necessary to subdivide the plant into its technical subsystems (e.g., energy supply, operating material supply, control technology, the conveyor system, delivery and supply systems, etc.). The next step is to identify possible fault scenarios for the individual subsystems and develop the appropriate countermeasures. Depending on their design, these countermeasures can enable qualitative assessments of the technical resilience of the system.

In production environments within the food industry, digitalization offers extensive opportunities to significantly improve resilience. This requires implementing the following measures:

- Identifying and using production data in the form of a digital twin
- Digitalization of processes
- Identifying potential incidents in production plants and overall systems (supply chains)
- Risk assessment
- Defining countermeasures
- Automating control of the plant using suitable sensor and actuator systems

Regional processing

Primary and secondary production processes are largely decoupled in the food value chain. This means that manufacturers of ingredients buy raw materials in bulk on the global market, and process these into a small number of products in highly optimized and specialized plants. As such, the main processing and value-creation processes do not take place at the site of the primary producer, or if they do, only to a limited extent. One current example of this is the production of vegetable oil: Both the raw materials (oilseeds) and the products (animal feed and vegetable oil) are traded and shipped worldwide. Normally, there is no direct link between the farmers that produce the raw materials and those that use the feed or process the materials in the oil mill.

To bolster regional value creation and increase the level of technological resilience, it is necessary to develop new processing concepts and machines that can both account for the variability of biological systems and their products or compensate for it. This requires modular, adaptive machine designs with the ability to process a variety of raw materials in a decentralized and resource-tolerant manner.

In addition to providing appropriate aggregates, food safety requirements also necessitate the installation of suitable sensor systems, ensuring the production of high-quality, safe food.

Global food security

Alternative cultivation systems

In additional to conventional agricultural methods, alternative cultivation methods for producing food, food ingredients and food supplements have been developed using closed systems, i.e., indoor farming; these could potentially contribute to global food security with such innovations as vertical farming processes for plants, insect cultivation, bioreactors for fungi, single-cell proteins, cultured meat and photobioreactors for microalgae.

There are many benefits to these methods: For one, they allow for year-round production processes that take place independently of global climatic conditions. This enables efficient and resilient production of food, and ensures consistent quality even in arid climates, marginal land and urban areas. Moreover, closed systems allow for controlled and safe processes - for example, compared to conventional agriculture, vertical farming requires only 5 percent less water and 50 percent less fertilizer to produce lettuce, herbs and protein crops such as cereals and alfalfa, and all without the use of pesticides [20]. In addition, thanks to their vertical structure and capacity for year-round production, these production systems are up to 100 times more productive per area used than conventional, horizontal agriculture.

Despite the many environmental advantages of vertical farming, the products it produces cost about three times more than those produced using conventional cultivation methods. This is mainly due to the high energy costs for lighting and air conditioning in the closed systems. Hybrid lighting systems, which combine sunlight with artificial light, are a possible method of reducing energy costs. Reducing energy consumption by using and coupling spectrally modulated light in vertical farming systems could significantly reduce costs, thus increasing the competitiveness of these systems.

Alternative protein sources

Obtaining 1 kg of animal protein through conventional animal farming (eggs, milk, meat) requires an average of 5 kg of protein from plant raw materials [38]. As such, the consumption of animal foods is accompanied by high levels of water and energy consumption and extensive use of agricultural land; it also accounts for a significant proportion of anthropogenic greenhouse gas emissions [39].

In terms of quantity, vegetable proteins are the most important alternative source of protein. However, the use of soy, currently the most widely used plant protein, must be questioned for sustainability reasons, unless regional production can be realized while protecting important ecosystems, for example in Europe. Moreover, the high allergenicity of soy significantly limits its use, and the same is true for wheat protein. As such, the recommended course of action is to produce new protein ingredients, preferably based on indigenous agricultural raw materials such as oilseeds and legumes. This requires developing adapted processes for producing highly functional protein concentrates and isolates with attractive sensory properties.

Compared to conventional animal protein sources, insects are comparatively efficient at putting their feed to use [40]. Insect farming could also potentially use biogenic residues as feed [41]. All this makes insect farming a sustainable system for producing high-protein food ingredients and animal feed [42].

However, in insect farming, the challenge is to avoid contamination with insect and foodborne pathogens (e.g., listeria or salmonella bacteria) in order to avoid the use of antibiotics and pesticides. To date, there are no suitable monitoring systems to protect “insect factories” from outbreaks of infectious diseases. Moreover, processing and preparation procedures for insect food products must be adapted to the needs of consumers and the food industry [43].

As with insects, filamentous fungi and microalgae are potential candidates for cascade utilization, where residues are used as substrates for cultivation. Another challenge is converting the proteins obtained from these raw materials into something palatable and marketing them as ingredients. In particular, establishing microalgae as a competitive source of protein requires technical advances in photobioreactors in terms of the efficiency of artificial lighting and AI-based system control and automation; what is more, the proteins must be processed into high-quality food.

In addition to these process-based measures, another key aspect of increasing resilience will be to develop more sophisticated methods of adapting organisms to changing environmental conditions (i.e., knowledge-based breeding of plants, microalgae and insects). This requires both prospective and preventive development expertise, taking into account how organisms could be cultivated and bred under demanding or even extreme conditions and anticipating future needs that will stem from this. Optimizing the process of reconditioning food, animal feed and raw materials begins with the organism used. Take starch potatoes for example - these have been adapted through selective mutagenesis processes (TILLING) in such a way that environmentally harmful chemical processes for reconditioning the starch became superfluous in industry. Adapting to growth in vertical farms or photobioreactors will also result in a more sustainable supply.

Increasing consumer acceptance by developing processes for alternative protein sources

Aside from the challenges of optimizing and improving cost efficiency in the production of alternative proteins, the use of these proteins in food presents another major hurdle. For instance, many vegetable proteins have a characteristic taste and coloration that consumers often find unfamiliar and

unpleasant. Moreover, the nutritional profiles of many alternative protein sources, in particular the proportions of essential amino acids and application-relevant (techno-functional) properties, are inadequate. In order to improve the sensory profile, further adjustments to production processes are needed, for instance to remove off-flavors or color-imparting components. In addition, using combinations of different proteins and ingredients should be further explored to exploit the synergistic effects of the proteins' functional properties and optimize their nutritional profiles.

Simplifying approval processes for novel foods

Regulatory requirements are another barrier to the use of new ingredients in food. For example, ingredients based on fungal mycelium, most insect species and many plants such as rapeseed require approval as "novel foods" by the European Food Safety Authority (EFSA). This takes a lot of time and money. What's more, it usually requires extensive studies on toxicological safety. However, an increasing number of companies now reject the animal testing processes required to carry out these studies. This is increasingly creating a barrier to further innovation and, as a result, food and food ingredients that are relevant to both the industry and consumers never enter the market. It is therefore advisable to simplify the approval process without compromising consumer safety.

Sustainable and healthy nutrition

Promotion of health and prevention of nutrition related diseases

The dietary habits of German citizens do not comply with recommendations by the German Nutrition Society (DGE). On average, people in Germany consume too much salt, sugar, saturated fats and animal products, and too few plant foods, particularly legumes. On the other hand, purely plant-based diets are not wholly recommended, as they only partially meet human dietary requirements - for example, they fail to provide the full spectrum of amino acids. In addition, they contain certain antinutritive constituents that actually make it more difficult for the body to absorb valuable nutrients.

Selective breeding, biotechnological approaches and targeted optimization of cultivation conditions can improve the sensory and nutritional profile of agricultural products as early as the primary production phase. These measures increase the proportions of valuable constituents such as proteins, vitamins and dietary fiber, as well as raising their value and reducing the proportion of unattractive sensory elements and antinutritive constituents.

In order to provide healthy foods that have high levels of consumer acceptance, new products must also be developed that are appealing to the senses. Mixing different ingredients (e.g., proteins, dietary fibers, etc.) will play an increasingly important role in compensating for the deficiencies in the sensory profiles, nutritional values and functionality of individual raw materials. This includes blending different plant raw materials as well as mixing plant raw materials with algae, fungi and animal sources, especially insects. However, consumer acceptance of insects as foodstuffs still requires improvement through targeted information campaigns.

When developing wholesome foods with optimized sensory properties, it must be remembered that consumer requirements in both areas are highly dependent on the consumer demographic. Sensory perceptions and nutritional profile requirements both depend on age, health status and lifestyle (e.g., stress levels, frequency of exercise, etc.) and are subject to cultural and regional influences. It is necessary to account for these different requirements when developing new foods and food ingredients, in order to provide products that meet all these needs.

The "NutriNet-Santé" study in France regularly collects the nutritional profiles of 300,000 individuals and the metabolic data of 20,000 consumers [44]. When collected as part of such a large cohort, this data can form the basis for developing digital, AI-powered tools for evidence-based nutritional counseling and can help provide consumers with individualized foods. However, the results can only be transferred to a limited extent due to differences in dietary habits, e.g., the significantly higher proportion of convenience foods in the German diet [45].

It is recommended that a study similar to "NutriNet-Santé" be carried out to determine the relationship between diet and diet-related diseases for German consumers in various demographics. Building upon this, it could be possible to develop digital tools and new foods to provide nutrition tailored to consumers' needs.

Handling avoidable and unavoidable food waste

Food production generates large quantities of unavoidable, i.e., non-consumable, by-products (e.g., peels, stalks, carcasses, etc.). Using these residues and side streams for energy and/or materials, ideally in a cascade model, has considerable potential for increasing value creation and resource efficiency.

Residues from plants, in particular, contain functional ingredients such as phenols, alkaloids, tannins, etc. These have great potential for use as basic chemicals, cosmetics, food supplements and food ingredients. However, this would require suitable concepts for providing the residues and side streams with the necessary level of quality. Similarly, integrated processes must be developed that extract functional ingredients while allowing the remaining matrix, which is usually rich in fiber, to be used as a source of materials (e.g., natural fiber-reinforced plastic composites) or energy.

In addition to the unavoidable waste mentioned above, a significant proportion of food waste is made up of products that, in principle, are edible. This includes vegetable and animal raw materials that are not sold or processed due to their shape, color or size. However, as these are basically edible, they can be used in the manufacture of food products for which the applied exclusion criteria play no or only a minor role (e.g., purees, smoothies, dried fruit and vegetable snacks, etc.). Since both the raw materials themselves (i.e., the type of fruits and vegetables) and their quantities vary greatly from season to season, highly flexible aggregates are needed to process these rejected and underutilized raw materials. Ideally, these would be deployed directly at the point of origin (e.g., logistics centers, processing plants) and be capable of processing both a variety of raw materials and various different quantities of materials into safe food. One option here is to use modular, adaptive machines equipped with appropriate sensors for quality assurance, which could be easily transported to other locations if necessary (e.g., during seasonal operation). However, there are currently no such processing machines available.

Food waste can be found throughout the value chain, with the largest amount of avoidable waste occurring at the retail and consumer level [46]. While waste flows can be effectively reduced during the production and distribution stages by optimizing processes and logistics, such purely technical solutions are largely inapplicable at the consumer level. As such, different measures must be combined here. This includes increasing the level of consumer education on the subject of avoiding food waste and creating the regulatory conditions to introduce measures such as a dynamic best-before date (BBD) or the use of antimicrobial coatings in packaging. In terms of technology, there is a particular need to introduce measures for extending and monitoring shelf life - this especially relates to developments in the packaging sector.

Currently, food packaging includes a static best-before date which provides a high safety factor. This means that the food normally has a much longer shelf life than is indicated by the best-before date. As consumers are not aware of the actual shelf life, they throw away large quantities of products that are still safe to consume. This can be remedied using low-cost sensors and indicators that monitor key food quality factors, e.g., compliance with the cold chain or the growth of spoilage products. This information could be expressed in the form of a dynamic best-before date (i.e., a built-in color scale on the packaging or a mobile app) to immediately inform consumers about whether the packaged product is consumable or not.

Composite materials are currently used to combine the properties of various materials, especially when it comes to packaging sensitive foods. This ensures that the packaged goods have the maximum possible shelf life; however, it prevents mechanical recycling of the packaging. One possible solution is to increase the functions of (bio-)plastic or paper-based substrates by applying (bio-based) coatings. Due to the comparatively low thickness of the layers, these coatings have little to no effect on the recyclability of the packaging; however, they must provide additional functionalities, e.g., creating a barrier against water vapor and oxygen or having an antimicrobial effect, in order to best possible protect the food and ensure it has a long or optimal shelf life. These types of coatings (especially bio-based coatings) and the packaging systems they create are currently only available in rudimentary form.

In addition to improving packaging systems and developing new packaging strategies, we also need to rethink the existing technologies and strategies for stockpiling, especially as they relate to a sustainable, circular bioeconomy. On the one hand, these are essential factors and drivers for securing supply, resilience and sovereignty in regional supply chains. At the same time, they guarantee that, in the event of large-scale crisis scenarios, there can be no spontaneous disruption and exploitation of ecosystems, disproportionate resource expenditures and emissions due to the relocation of transport routes, or the restriction of food supplies as a result of warlike or criminal elements. The highest priority must be given to diversifying the strategies and systems for stockpiling, taking into account factors such as food quality and the nutritional and sensory value of the products. At the same time, stockpiling processes must be managed in such a way that inventories can be kept up to date and aligned with demand. Moreover, the corresponding foresight processes and scenario analyses must be kept constantly up to date and account for current environmental, economic, social and political developments.

Material use of biomass and CO_2

From the linear value chain to the value cycle

The circular bioeconomy is based on the production, use and end-of-life management (i.e., reuse, recycling) of products containing carbon; as such, it is closely tied to the global carbon cycle. Losses in the cycle can be attributed to material losses during the manufacturing and use phases, as well as biogenic degradation. Probably one of the oldest and best-known examples of a value creation cycle is the paper production process. The main component used in paper production is cellulose obtained from wood, a renewable raw material. Nowadays, used paper is recycled and waste paper fibers are reused in paper production, thus closing the loop.

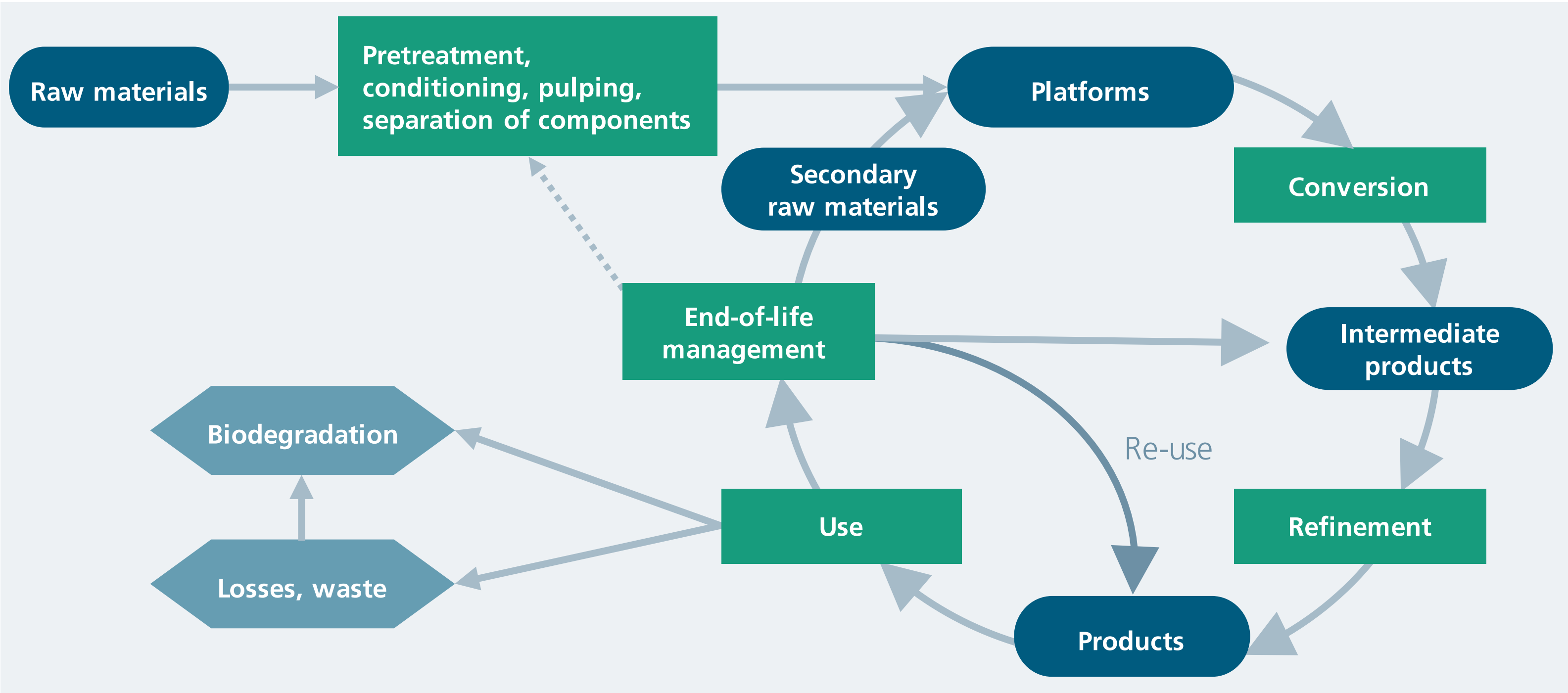
Bioeconomy can also offer an advantage when complex molecules or structures are produced via shorter (e.g., biotechnological) conversion routes compared to conventional (chemical) processes. Residues should be used for this purpose if possible. In addition, bioeconomic processes enable integrating CO_2 into a value creation cycle, allowing for both the indirect and direct use of CO_2.

Figure 3 demonstrates essential elements of the circular bioeconomy and provides some examples of the respective process stages, raw materials and products.

The challenges and development needs that the circular bioeconomy faces are illustrated below with examples of value creation cycles. These include, among others:

1. Bio-based plastics
2. Biomaterials as building materials
3. CO_2 as a raw material
4. Chemical raw materials and fuels produced though thermo-chemical processes

Fig. 3 Bioeconomy value creation cycle with examples of the respective process stages (green), raw materials and products (blue)



Pre-processing
- Biomass fractionation
- Cultivation
- Extraction
- Thermochemical conversion

Conversion
- Chemical derivatization
- Fermentation
- Polymerization
- Catalysts

Refinement
- Downstream/Separation of materials
- Formulation including additivation
- Processing, forming, spinning
- Purification

End-of-life management
- Collection/Sorting
- Chemical recycling
- Physical recycling
- Mechanical recycling

Raw materials:
- Plant-based biomass
- Biogenic residual materials
- CO_2
- Animal-based biomass

Intermediate products
- Polymers
- Resins
- Modified polysaccharides and proteins
- Chemicals

Platforms
- (polymeric) Carbohydrates
- Lignin
- Proteins
- Chitin
- Fats/oils
- Specialty chemicals
- Carbonisates
- Synthesis gases

Products
- Molded parts
- Composites
- Binders
- Lubricants, fuels
- Food/animal feed

Bio-based plastics

Production process

The process of producing plastics from biomass, their use and recycling represents a value creation cycle for the bioeconomy, which can be depicted as follows for bio-based thermoplastics: Various platform chemicals are obtained from raw materials in the form of monomer building blocks; these are then used to synthesize the bio-based polymers (plastics). During an interim step (compounding), the plastics can be modified for specific applications or used directly. The loop is closed when the durable components are re-used, or the appropriate recycling processes take place. There are already qualified systems established on the market for all the processing steps within the value creation cycle. In addition, there are a number of developments with different technology readiness levels (TRL), which will be discussed below.

Current state of technology

Currently, the search for sustainable raw material sources is focused on cellulosic and lignocellulosic residues and materials that are available in larger quantities. An example is the renewable raw material wood, including all its components, as well as similar lignin-containing biomass from agricultural by-products such as wheat straw [47]. The health of the soil must be taken into account here, as intensive crop cultivation leads to nutrient loss. This must be compensated for by using humus-forming measures to ensure the soil remains fertile and retains its ability to store water, thereby producing good yields. Another possibility is using residues containing cellulose from the paper manufacturing industry. One future goal is to expand the raw material base for plastics to include CO_2 as a primary component, although the technology for this is still in the early stages of development (TRL of 2 - 4). There are numerous technologies available to help break down lignocellulose, a component of the cell wall of lignified plants (wood, straw, etc.); however, these must be individually adapted to each type of biomass. In addition to long-established pulping processes used in pulp mills, new processes such as “steam explosion” (i.e., steam pressure pulping) or “organosolv” (solubilization via organic solvents) have been either developed or rediscovered, especially in the context of biorefinery approaches [48].

The fractionation of lignocellulose into its main components, cellulose (C6 sugar), hemicellulose (C5 sugar) and lignin (aromatic compounds), is an essential requirement for its full, high-value material utilization as a renewable chemical raw material. For example, glucose is obtained from cellulose through enzymatic hydrolysis. This can be used as a substrate for a variety of fermentations, thereby replacing the higher-value raw material sources currently used, such as sugar cane and starch [49]. During fermentation, microorganisms such as bacteria and fungi metabolize these carbon compounds and convert them into both biomass and a variety of chemicals, including ethanol (which is further processed into ethene), succinic acid, butanediol or lactic acid, which can then be further processed into polymers such as bio-polyethylene (bio-PE), polybutylene succinate (PBS) and polylactic acid (PLA) [50]. Various polymers such as polyhydroxybutyrate (PHB) can also be obtained directly from sugar by means of fermentation. When it comes to lactic acid, the processes have been developed to such an extent that PLA can be produced entirely bio-based under economically competitive conditions. Around 300,000 tons of PLA are produced annually by means of fermentation [51].

Further on in the value creation cycle, the chemically or biotechnologically produced polymer can be combined with other polymers or additives (for instance, stabilizers, processing aids or even flame retardants), as well as fibers, from natural fibers to bio-based carbon fibers, to obtain a wide variety of material properties for the subsequent plastic components. At present, two types of bioplastics can be identified as having the potential to replace conventional petroleum-based plastics on a larger industrial scale and in a wide range of applications: PBS and PLA. Both materials are currently undergoing extensive further development processes; by improving their existing property profiles and increasing the variety of types, the processes aim to make these plastics suitable for more fields of application, up to the level of engineering plastics. For example, as it stands, water filters (PBS), coffee capsules (PLA), storage containers (PBS) and electronic components have already been developed to a state of market maturity. Development work in other fields (blow molding, thermoforming, etc.) has also advanced a long way. In the field of packaging materials, soft materials have been developed from PLA by adapting its molecular structure [52]. Thanks to the development of suitable formulations, PBS and PLA materials can already be used today for durable injection-molded components; these components are impact-resistant, temperature-resistant and flame-retardant [53]. In principle, all known processing technologies used for conventional, fossil-based plastics can also be used for processing bioplastics. Bioplastics have great potential. There are already many possible applications for bioplastics, and specific adaptations for additional, higher value applications are showing promising results.

After use, the material that makes up the component can be reintroduced into the value creation cycle through recycling. Various processes can be used to do this, depending on the bio-based plastic in question: Mechanical recycling recovers the polymer directly, whereas in chemical recycling processes it is first broken down into small building blocks that can then be re-used for polymerization, thereby completing the cycle [54].

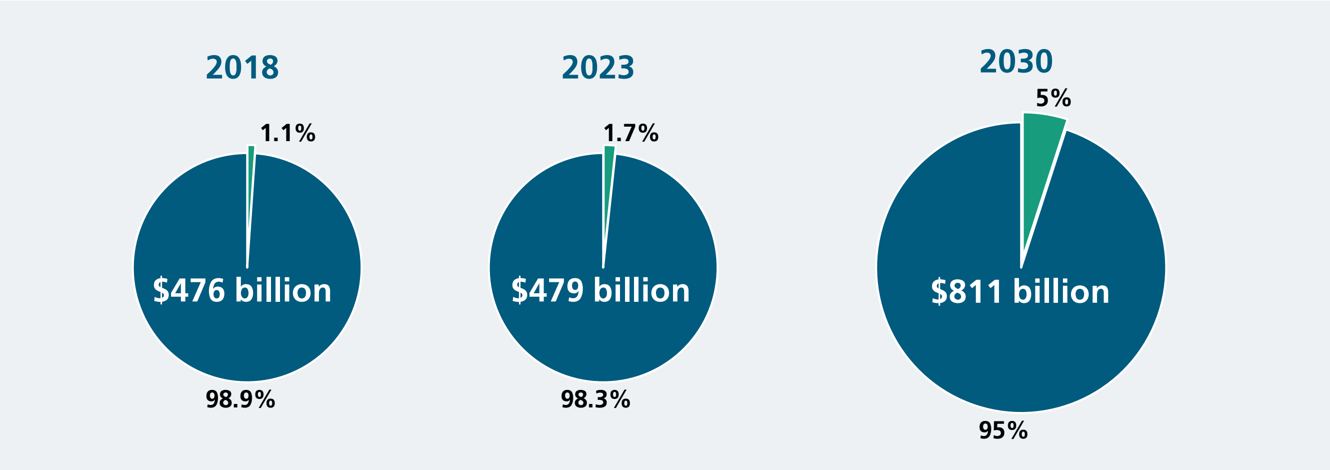


Fig. 4 Global market shares of bioplastics by revenue from 2018, as well as estimates for 2023 and 2030: Bio-based plastics and petroleum-based biodegradable plastics [60–62]

Many bio-based plastics are also biodegradable, giving them the advantage of returning cycle losses to the carbon cycle through an additional biodegradation process - all without "littering" the biosphere. However, this direct, purposefully controlled biodegradation route is only relevant to a few applications (e.g., various agricultural products or "liquid" plastics in cosmetics); moreover, it should only be implemented in cases where recycling is not possible [55].

Issues and challenges to overcome

In 2020, plastics production worldwide amounted to approximately 367 million tons, not including fibers made from polyethylene terephthalate (PET), polyamide (PA) and polyacrylonitrile (PAN) [56]. Plastics production processes are responsible for about 6 percent of the global demand for crude oil [57]. In some cases, toxic substances of concern are used, some of which are released during the use phase of the plastic (bisphenol-A (BPA), isocyanates, etc.). According to estimates, approximately 8,300 million tons of petroleum-based plastics were produced up to the year 2017, of which approximately 5,000 million tons ended up as waste, both in landfills and in the wider environment [58].

Bio-based and biodegradable plastics, on the other hand, account for only a very small share of current global plastics production (fig. 4), with estimates ranging from about 2.4 to 3.8 million tons, depending on the applications taken into account - this falls within a range of about 1 percent. However, current forecasts predict that production capacity will vastly increase to 7.5 million tons by 2026, with most of this expansion taking place in Asia [59]. The most important bio-based polymers used to manufacture bio-based plastics are PBS, PLA, starch blends, bio-based polyamides (PA) and bio-based polyethylene (PE). Currently, there is also a noticeable trend of manufacturers of conventional plastics buying pre-processed bio-based raw materials, particularly bio-naphtha. This is then processed together with the petrochemical naphtha. The portion of the standard polymers produced from this, which corresponds to the proportion of bio-naphtha in the raw materials, is then marketed as being bio-based in accordance with a mass balance approach.

As of yet, the potential of bio-based plastics for achieving sustainability has not been sufficiently exploited, due to the low quantities of these plastics in the market. This is particularly true in the recycling industry. Implementing existing technical solutions and innovative recycling approaches requires the relevant political guidelines to be adapted and access to the market to be facilitated; this will not only help close the recycling loops, but will be economically competitive and ensure that the environmental advantages of bio-based plastics are fully exploited. For example, if the advantages of bio-based plastics in terms of carbon footprint also resulted in a competitive price, then it would bolster the technological development. This could be achieved through measures such as carbon pricing and other climate protection charges. Essential education on the options for using and recycling bio-based plastics, including potentially biodegradable plastics, can also lead to broader acceptance and demand.

However, realizing much-needed innovations within the entire value creation cycle, including raw material extraction, processing and recycling, is essential for the wider use of bio-based plastics in various applications. This is the only way that bioplastics can catch up with conventional plastics from an economical and technical perspective and become established on the market. As such, the research and development needs for bioplastics are briefly outlined below.

Research and development needs

Improved sustainability in the plastics industry is an issue of great importance in almost all sectors of society; in the context of further developing a bio-based plastics economy, the main technical challenges are in the following areas

- Bio-based raw materials (agricultural products, wood, natural fibers, residues, etc.)
- Expanding the material property profile and processing procedures
- Integrating biological functions into plastics in order to expand their range of applications and increase circularity
- Developing recyclable and biodegradable plastics to combat "littering" with a view to a comprehensive circular economy
- New recycling technologies

Where possible, low-cost carbon sources such as lignocellulose or storage carbohydrates such as inulin should be used as raw materials for bio-based plastics and should be the focus of research. At the same time, we must promote the development of more powerful microorganisms, for example, through new, advanced genome editing tools, and continue the search for new microorganisms in order to broaden the range of achievable, necessary products. There are obstacles both in terms of legislation and the public, who still have a low level of acceptance for the use of genetically modified organisms.

Plastics made from biogenic materials are a relatively young class of materials when compared to their relatives made from fossil raw materials. Specialized (bio-based) additives, compounds and processing technologies have not yet been developed; in contrast to petrochemical materials, which have been available for over 50 years. As a result, bioplastics cannot match conventional plastics in many areas of their property profile, although efforts have been made to close the gap. Further development of both the biopolymers themselves and new bio-based additives and formulations will help solve issues concerning the enhancement of the melt viscosity and expansion of Young's modulus as well as the elongation-at-break ranges for all applications currently covered by polyolefins. Increasing the heat distortion temperature of PLA and improving the barrier of bio-based plastics against oxygen, water vapor and odorants are also needed.

We must therefore work to continuously improve technologies for modifying and broadening market qualities. This must be accompanied by an evaluation of new polymer components in terms of their material properties and from an economical perspective and in regard to life cycle analysis (LCA). Circular solutions must be developed, including processes for recycling other (bio-based) plastics; these must be evaluated accordingly and must be put through practical tests to prove their effectiveness. There are a number of requirements here for collecting, separating and reconditioning materials as well as for the development of both depolymerization processes with downstream processing and repolymerization processes.

Biomaterials as building materials: fungal materials

Issues and challenges to overcome

The construction industry accounts for more than 10 percent of the German GDP and is therefore a significant sector of the German economy [63]. Ensuring resource efficiency and introducing sustainable raw materials, recycling and climate-neutral energy supplies in both new and existing buildings are all essential steps toward achieving a climate-neutral construction industry. Using bio-based raw materials, including fungus-based materials or hemp, in place of primarily fossil raw materials will be crucial for reducing the carbon footprint of products and implementing new material cycles in construction.

Fungi represent a starting point for developing new sustainable materials that can be used in the construction industry, e.g., as insulation. They are natural models for recycling and reevaluating organic waste materials. In nature, they pervade their food source, the substrate, using their network of cell threads known as a mycelium. Substrates consisting of loose fibers can be joined by the thread-like cell filaments (hyphae), with the mycelium forming a solid composite from the fibers. Wood-decomposing fungal species, in particular, are already being used to produce insulation and packaging materials and for textile applications. These fungus-based materials can be divided into two material groups: First, there are composite materials, where the substrate is still present within the material in its final state; then, there are materials that just consist of the pure mycelium after the manufacturing process (this is often known as mushroom leather) [64–66]. In the case of composites, fungal mycelium, which does not contain formaldehyde, is used as a natural binder to produce biodegradable materials. A wide variety of organic residues from industrial processes, agriculture and the wood industry can be used for both material groups. As a non-toxic, entirely compostable material based on residues and waste materials, mycelial materials are particularly suited for use in a bio-based circular economy.

Production process

When it comes to fungus-based materials, the production process can be roughly divided into four process steps: preparation, growth, deactivation and post-treatment. The desired organism is grown as a stock culture in a nutrient medium and a sterile substrate (liquid or solid) is inoculated. Depending on the type of fungus, different plant residues can be used as the substrate, such as straw, pomace, green waste, etc. Following inoculation, the mycelium begins to pervade the substrate. This process can take one to three weeks, depending on environmental conditions and the type of fungus. In the case of pure mycelial materials, conditions are chosen that will ensure the mycelium grows more on the substrate and less in the substrate. For composites, the hyphae need to penetrate the substrate, as they are to become part of the material. As one option, composites can be grown in the desired product form. More often, however, the composite is pre-grown and is crushed once the mycelium has grown through the substrate. The crushed particles are then being poured into negative molds and within a few days the mycelium continues growing and a solid structure is formed in the mold. In addition to molding using negative molds, fungus-based materials can also be produced using paste-like substrates as part of a 3D-paste printing process [65]. In this case, the fungus pervades the 3D-printed paste, improving the stability and water-repellent properties (hydrophobicity) of the products. Regardless of the manufacturing process, fungal growth must be stopped prior to the formation of fruiting bodies in order to prevent changes in the material properties and the spread of the growth to other lignocellulosic materials in the vicinity. To this end, fungus-based materials are dried under elevated temperatures at the end of the growth process. Fungus-based materials may have to be post-treated, depending on the area of application. If pure mushroom mycelium is used in textile applications, it must be made more durable and flexible, much like animal leather. Composite materials are also subject to special requirements depending on the application, from fire-retardancy to moisture resistance. Aside from adapting the functionality, there are other possibilities such as dyeing or embossing the various materials.

Research and development needs

The entire process of manufacturing fungus-based materials is relatively new at this point and in need of optimization. On a laboratory scale, all steps of this process chain are currently carried out manually. Since the raw material costs are very low, the materials and subsequent products can be produced more efficiently by scaling up and automating the production steps. From both an economic and environmental point of view, there is an increased need to optimize the process of growing fungal mycelium, especially when it comes to the amount of energy consumed by the required air conditioning technology. In the textile and construction industries, the process technology necessary for this is not available, as these sectors do not yet use partially sterilized or air-conditioned production processes. This makes it more difficult to scale processes up to industry levels and increases the need for R&D. Going forward, the production processes familiar to the biotechnology and food industries will have to serve as starting points for new production routes. In the construction industry, in particular, there is still a negative connotation to fungi: as they are associated with mold in buildings, there are concerns about their spread. Addressing these concerns will require increased educational work. Moreover, in production processes involving living organisms, quality fluctuation always poses a challenge. This is already a known issue in the textiles sector because it affects the leather industry. The construction industry is built around standards, with little leeway. This means more research is required on how these processes can be implemented while ensuring quality and avoiding losses caused by quality fluctuations. Variations in quality are also a concern when it comes to raw material security: An advantage of fungi is their ability to grow on different substrates, but the potential variance of this biological system must be taken into account by introducing technological measures, adapting assessment systems, reconsidering existing norms and standards and adapting regulations. To ensure the future-proof production of fungus-based biomaterials, it would certainly be beneficial to develop production processes that can use a variety of plant residues as starting substrates. However, this must also be facilitated by appropriate regulatory frameworks, especially in the testing and exploratory phases.

CO_2 as raw material

Issues and challenges to overcome

In recent decades, the concentration of carbon dioxide (CO_2) in the atmosphere has been higher than it has been for hundreds of thousands of years. In 2021, 36.3 billion tons of CO_2 equivalents were emitted worldwide due to the combustion of fossil fuels for energy and industrial processes [67, 68]. These CO_2 emissions are far too high and must be significantly reduced in order to limit the effects of climate change. Germany is committed to achieving net neutrality for greenhouse gases by 2045 and is aiming for negative greenhouse gas emissions after 2050 [69]. Drastic reductions in CO_2 emissions are required across all sectors (energy, industry, buildings, transportation, agriculture and waste management) on the way to achieving this goal.

Increasing efficiency and conserving energy are two important solution strategies; another is defossilization, i.e., increasingly replacing fossil energy and raw material sources with other raw materials. In the future, CO_2 will play an important role here. At the same time, it is becoming increasingly clear that in order to achieve the global 1.5 degree target (i.e., limiting the rise in the mean temperature worldwide to a maximum of 1.5 degrees above pre-industrial temperatures), the remaining CO_2 budget will be used up much sooner and more CO_2 will also have to be actively removed from the atmosphere and captured [70, 71].

Production process

Scientists in the fields of chemistry, process engineering and synthetic biotechnology are working closely together to offer intelligent solutions for efficiently capturing, purifying and utilizing CO_2. The aim is to further develop the technologies into economically viable models. Different routes for the use of CO_2 in terms of the bioeconomy, i.e., as a forward-looking alternative to fossil carbon sources, are outlined below.

Improving the conversion of CO_2 into biomass and valuable ingredients using terrestrial plants remains a high priority. Cultivating microalgae, for example, offers another direct route for utilizing CO_2. They require CO_2 for growth, and as such, can convert carbon from the atmosphere directly into a variety of innovative products with high added value.

Another chemical-synthetic approach involves converting CO_2 and hydrogen into methanol, wherein the hydrogen is produced via a PtX production route powered by renewable energy. Uses for the methanol include further synthesizing drop-in fuels or producing platform chemicals for the chemical industry of tomorrow (fig. 5).

Current state of technology

Examples of products that are already being directly extracted from microalgae include algae oils and fatty acids. These can either used in the form of algae fuels for energy purposes or for producing plastics, e.g., algae-based thread for the textiles industry [72]. Particularly in applications where the carbon is bound in the product for a longer period of time, algae biotechnology is showing enormous potential as a carbon sink. For example, the production of 1 kg of algal biomass actively removes 1.8 kg of CO_2 from the atmosphere [73]. Microalgae are also excellent producers of valuable dietary supplements, such as the carotenoid astaxanthin. They can also be used to produce proteins, and could therefore provide an efficient, sustainable food supply for the growing global population (see chapter “Food”) [74].

Using the PtX approach, methanol can be directly produced from CO_2 as the primary intermediate product. In a subsequent process, this methanol is converted into other intermediate products to finally form liquid fuels from the gasoline and middle distillate fraction. This is known as the methanol route, and it offers the possibility of developing sustainable, CO_2-neutral drop-in fuels, also known as e-fuels, that can be used in areas where electromobility is not an option. Such areas include agricultural and forestry machinery and inland shipping, as well as commercial aviation and heavy goods transportation.

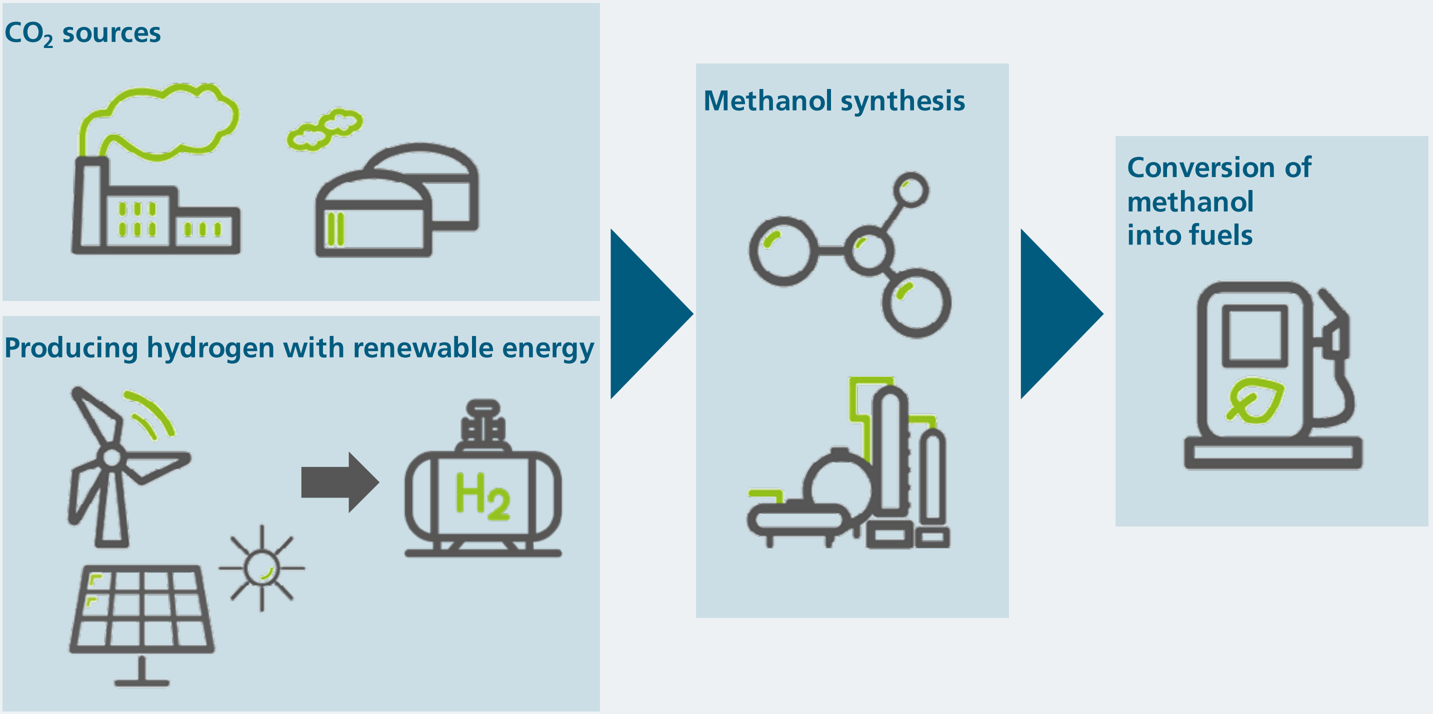


Fig. 5 Producing sustainable CO_2-based fuels using the intermediate product methanol

Methanol synthesis is an industrial-scale process (TRL 9); the largest (world-scale) plants currently have a capacity of around 7,200 tons per day. In 2019, approximately 90 million tons of methanol were produced worldwide. Industrial methanol synthesis uses fossil or biogenic synthesis gas (a mixture of hydrogen and carbon monoxide (CO)) as a base material. The aim is to produce green methanol exclusively from CO_2, e.g., from industrial point sources (waste gas emissions from cement plants, biorefineries, etc.), and green hydrogen produced from water using electrolysis.

Research and development needs

In order to make algae biotechnologies economical for a wider range of applications, particularly in the targeted lower price bracket, more efficient reactor systems for cultivating the algae are required, along with optimization of the production processes [75]. Due to developments in the field of LED technology, algae cultivation is currently transitioning from taking place outdoors to indoors under artificial lighting [76]. Depending on the location and the technology used, some artificially lit cultures are already proving more profitable than those "cultivated" out in the open. In order to achieve maximum efficiency, it is not only important to continue driving developments in LED technology to maximize the yield of light per unit of energy, but also to use new reactor designs to improve the yield of biomass per unit of light. There are currently only a few algae biotechnology products, and these are in a higher price bracket. One particular factor standing in the way of advancements in this area is that genetic engineering tools are required to enable targeted development of biotechnologically modified high-yield algae. However, these tools are not yet been sufficiently established or available [77].

In addition, improving the utilization of CO_2 in terrestrial plants and its conversion into raw materials (sucrose, starch, inulin, natural rubber, etc.) could result huge leaps forward in the bioeconomy, in terms of the provision of recyclable materials for many industries.

An important aspect for direct chemical-synthetic use of CO_2 involves using the methanol produced from the CO_2 for subsequent biotechnological processes; this is an alternative to the more typical route whereby it is used in the chemical industry. In the alternative route, methanol is used instead of sugar as a source of carbon and energy for microorganisms. Thanks to metabolic engineering, these microorganisms can synthesize valuable chemical products. This method combines PtX approaches with the field of industrial biotechnology. However, given the wide range of possibilities such a method opens up, the term "PtX" is not broad enough, as electrochemical conversion only represents the first step in the subsequent process chains. This concept has therefore been given the expanded name "Power-to-X-to-Y," to indicate that this rapidly evolving approach to recycling CO_2 using renewable energy is not limited to synthesizing simple products ("X") such as hydrogen or methanol. Instead, these simple products are expected to serve as raw materials for refineries in the future, where the new platform chemicals ("Y") we so urgently need will be produced using various cascading processes.

When it comes to direct methanol synthesis from CO_2, there are still a number of challenges standing in the way of development. The studies carried out so far have primarily used conventional catalysts that react very sensitively to catalyst poisons that occur as impurities in industrial CO_2 sources, such as combustion and fermentation processes. In this area, there is a need to develop stable, resilient catalysts for CO_2-based methanol synthesis processes [78]. In order to expand our knowledge of gas processing and process stability and performance, it is necessary to conduct more studies in which methanol synthesis processes that use a variety of industry CO_2 sources are taken into account. These studies should be carried out under the most realistic process conditions possible in order to more easily transfer the findings to industrial application.

A pre-industrial plant for producing CO_2-based methanol was built in Iceland in 2012 [79], and additional, similar plants are in the planning phase. Reliable pilot-scale studies are required to support these developments and enable stable, selective synthesis on an industrial scale and using a variety of industry CO_2 sources.

Thermochemical conversion of biomass

Production process

Thermochemical production of chemical raw materials and sustainable fuels from biogenic residues (e.g., from agriculture and forestry, the food industry and algae cultivation) forms a bioeconomy value chain consisting of the following stages: Biogenic residues are converted through thermochemical processes (pyrolysis, gasification, hydrothermal carbonization) into intermediate products such as biochar (carbonisates), pyrolysis condensate, pyrolysis coke and synthesis gas. These intermediate products are then utilized in further process steps and applications. When it comes to the carbonisates and the pyrolysis coke, this includes utilization as a material (soil application, aggregates for building materials, etc.), which also enables long-term carbon storage, and utilization as an energy source. Depending on its quality, the pyrolysis condensate (pyrolysis oil) can be refined into a fuel via various post-treatment steps or used in refinery processes. In the case of synthesis gas, direct energy use is possible, as is synthesis into methane (SNG, Substitute Natural Gas), methanol or Fischer-Tropsch hydrocarbons [80]. By adding green hydrogen to the primary synthesis gas, an almost complete recovery of carbon from the feedstocks can be achieved.

Issues and challenges to overcome

The main challenge associated with these processes is finding an economically valuable means of converting biogenic residual flows, which are currently relegated to low-value commercialization pathways, or not utilized at all. In recent years, huge advancements have been made in technologies for the thermochemical conversion of residues. In thermo-catalytic reforming (TCR), for example, thermally stable oils can be produced as intermediate products that can then be hydrogenated to form fuels [81, 82].

In general, when it comes to the future use of energy-based fuels (Power-to-Liquids (PtL) fuels), it is expected that a mixture of biofuels derived from waste materials will be recommended for costing reasons and to broaden the range of raw materials available. However, in practice, mixing fuels is a complex process, and it can be necessary to develop special additives for each case. An early experimental approach to solving this issue while taking environmental and economic factors into account could help significantly accelerate the German federal government’s planned implementation of PtL fuels for shipping and potentially also heavy goods transportation and reduce economic barriers [83].

Current state of technology

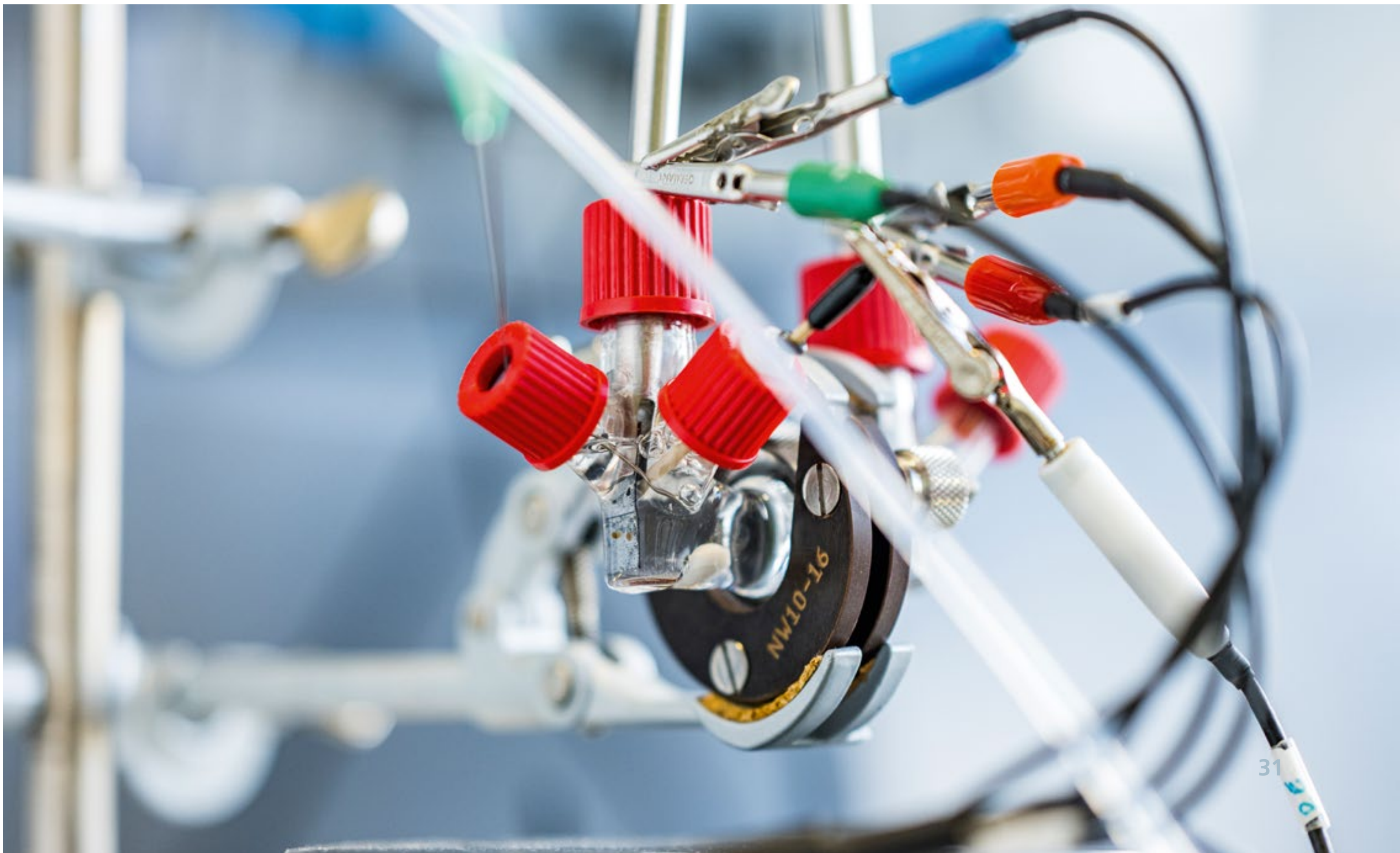
The different pyrolysis and gasification technologies must be optimized in terms of scaling and flexibility, depending on the raw material used. For example, it has been demonstrated that sewage sludge can be recycled to produce sustainable fuels. A pyrolysis-based conversion technology has been used to produce thermally stable bio-oil, which then undergoes hydrogenation to bring it up to the quality levels of standard fuels.

Bio-oil produced through rapid pyrolysis of straw and energy grasses can be converted into an intermediate product, which can then be incorporated into the processes of a conventional crude oil refinery; this has already been demonstrated on a large pilot scale. Other components can also be produced from straw and agricultural residues; once supplemented with additives, these can be used as conventional fuels for shipping.

Research and development needs

When it comes to technological optimization, the focus is on broadening the range of raw materials used. In particular, this includes sources of biomass residues that have not been prioritized for investigation in the past due to their high ash content or heterogeneous composition; however, the fact that these materials are readily available means that they will be important. In addition, the processes must undergo technical simplification, in order to ultimately reduce both the level of process management required and, in particular, the cost of the product gas line, so as to make them economically viable. Product properties also constitute a key parameter for process optimization, in order to provide high-quality synthesis gases, pyrolysis oils and carbonisates [84]. Developments in process engineering in recent years have also enabled bio-oils produced through thermochemical conversion to be used in new, high-quality applications. Most notable here is the hydrogenation of pyrolysis oils, which can be processed to form valuable (intermediate) products thanks to improved oil properties. It is to be investigated, among other things, with a view to using the oils and intermediates produced directly in the refinery process and the chemical industry or for the production of blended fuels on a PtL basis with thermochemically and otherwise produced residual biomass-derived fuels.

To enable continued development, it is crucial to assess the value chains for commercializing residues in their entirety, in terms of industry, sustainability and socio-economic factors. Such an assessment will be vital for scaling up processes (for example, certain issues must be addressed in this context as regards the reduction of specific costs vs. the availability and transportation of residues).



Excursus:
Biological Transformation

The biological transformation is an important element on the way to implementing a circular bioeconomy. Biological transformation is defined as increasing the use of materials, structures, processes and organisms of living nature in technology and production in order to achieve sustainable value creation. In this context, three distinct modes of development for transformation processes have been identified. In bio-inspired systems, biological concepts or phenomena serve as inspiration for technical systems. By contrast, bio-integrated systems involve at least one biological component, such as an enzyme or, in more complex cases, a cell, being combined with a technical system. In a bio-intelligent system, an informational system (e.g., AI) is added to a bio-integrated system, enabling interaction and communication between the biological and technical systems [85–87].

Rather than just involving one key technology, the biological transformation combines many different innovations from life sciences, engineering and information sciences [85, 86]. On this basis, researchers are currently working to develop and process bio-based, bio-inspired and bio-integrated materials, among other things [85, 86, 88–90]. Bio-intelligent waste-to-X systems are also playing a major role in the biological transformation. These systems allow the valorization of residues and waste materials through reuse, along with the recycling of materials and energy carriers [85, 86, 91–93].

Intersections are created between biology and technology (e.g., sensor and actuator systems) for the purpose of transferring data between biological and technical systems [85, 86, 94, 95]. Tools such as digital twins and bio-inspired algorithms are required for the development and management of bio-intelligent production engineering systems. Huge volumes of data are generated to enable interactions between biological and technical systems, which could be managed by bio-inspired and bio-based data processing systems [85, 86].

Another area of biological transformation involves bio-intelligent energy generation, storage and supply. Various research approaches have been adopted in this context, from artificial photosynthesis to hydrogen bioenergy with carbon capture and storage (HyBECCS) processes [85, 86, 92, 93, 96]. In addition, developing models to map complex bio-intelligent systems and predict the impact and consequences of bio-intelligent technologies is a key factor for ensuring that these systems are safe and controllable. With regard to the use of genetically modified organisms, Artificial Intelligence and personal data in bio-intelligent systems, fundamental ethical questions still need to be clarified and security measures developed [85, 86].

To summarize, it can be noted that bio-intelligent systems have reached various stages of development, ranging from the initial descriptions of use cases to the deployment of prototypes. However, if these systems are to become more widespread, and pilot technologies are to be transferred to industrial production, more intensive applied research is required in this field.

Recommendations for action

To make the bioeconomy a reality for society as a whole, the right conditions must be put in place in academia, industry and society, so as to create a lasting, reliable and predictable environment for research, development, innovation, production and the provision of services.

It is imperative that the transformation of the economic system from linear to circular processes is implemented across every level of society. This will call for a variety of specialized initiatives, from providing information to a dialogue with society that will help achieve the required acceptance for the bioeconomy.

The circular bioeconomy is crucial for securing and improving the German economy's competitive position for the future, and to achieve the ambitious national, European and international targets for climate protection and sustainability. The strategic foundations for a sustainable, bioeconomic system have been laid down through the European Bioeconomy Strategy, the German National Bioeconomy Strategy and a range of bioeconomy strategies by the German federal states and regions. The transformation to circular, bioeconomic processes needs reliable, supportive political conditions and specific measures. This is the only way to actively drive the necessary processes forward, with society as the driving force.

Systemically translating innovations (both existing and future) into real-world industrial applications is particularly important here. It is vital to continuously review the measures adopted, in order to implement the bioeconomy and, where necessary, to adapt them to changing conditions and develop them further. This is essential for achieving environmental, economic and social sustainability targets with a circular bioeconomy.

The Fraunhofer-Gesellschaft has set out short-term (up to 2025), medium-term (up to 2030) and long-term (up to 2035) recommendations for implementing and establishing a circular bioeconomy, which are outlined in the following section. The recommendations are divided into three topics: framework conditions, technologies and translation.

Framework conditions

Short-term implementation

As our raw materials are limited, our current consumption levels and the associated use of resources cannot continue as they are, much less be allowed to increase. This unsustainable behavior has drastic consequences that at this point will be difficult - if not impossible - to reverse (climate change, biodiversity loss, etc.). Immediate action must be taken in the form of short-term measures. These include systematically transferring existing, established circular and bioeconomic technologies, processes and products to industrial application. These have not reached industry level yet, due to path dependencies, lack of competitiveness and high costs. Above all, we therefore need to create framework conditions that allow the advantages of bioeconomic circular products and processes to be reflected in a positive economic impact. In addition, we must place great emphasis on implementing centralized and decentralized processing technologies and models, such as biorefineries, to enable sustainable technologies to evolve from pilot scale to industrial implementation. The necessary regulatory conditions must be adapted or created from scratch, and regulatory barriers must be removed where necessary. New Living Labs must be established in the bioeconomy field to provide test spaces for innovations and regulations. This will give industry and researchers the chance to jointly explore services, products and approaches that only conform to the current legal and regulatory conditions to a limited extent.

If implementation is sped up, companies must be given planning security and financial risks must be cushioned. For this to happen, however, the barriers blocking commercialization must be removed. Early involvement of industry in the R&D process makes it possible to focus on market-driven development. When it comes to technology transfer, particular attention must be paid to improving access to capital-intensive infrastructure by establishing pilot and prototype plants. There must also be a focus on improving access to existing infrastructures and upgrading the services they provide. To provide companies incentives for the adoption of bioeconomic technologies, options such as subsidies and tax contributions for meeting environmental standards could be considered. These incentives, however, need to consider environmental production standards, the compatibility with a circular economy and the benefits of sustainability.

It is also important to initiate and drive progress regarding new technologies. For this to happen, the German federal and state governments must continue to provide targeted funding - ideally in an interlinked and coordinated manner across ministries. This approach should also line up with EU-level bioeconomy strategies and activities.

Medium-term implementation

Bioeconomic processes and products are not sustainable per se. It is therefore crucial to use a methodologically sound approach to determine the advantages of bioeconomic processes and products compared to conventional processes and products from a sustainability perspective. These advantages must be communicated in a transparent, comprehensible manner. Sustainability assessment criteria and suitable metrics must be developed and standardized. This will enable comparison of different assessment approaches and allow the sustainability of products to be made more visible in the market. These metrics, which will primarily be designed to assess reliability and longevity, will ensure that intentional, effective decisions are made in both the business-to-business (B2B) and business-to-consumer (B2C) sectors regarding sustainable processes and products. Sustainability profiles should be communicated in a transparent way, in order to increase the demand for sustainable products and services. In terms of climate policy, such types of metrics have been established for CO_2 pricing and European emissions trading. When it comes to harnessing and utilizing residues and the products manufactured from them, a system is required that directs biomass and residues toward the most advantageous usage path in each case. Assessments, relevant metrics and analyses are needed here, so that valid conclusions can be formed as to which of the potentially possible commercialization methods are preferable in the given context. It is also necessary to reassess the term “waste”, particularly when it comes to definitions stipulating when a product ceases to count as waste, and the associated regulations and laws. This will enable extensive recycling of residues in bioeconomic processes.

Specific regulatory frameworks will help facilitate market entry for bioeconomic products and technologies. Voluntary commitments, standards, quotas and subsidies will play an important role here. These must be strictly linked to sustainability assessments. The aim is to create a level playing field, whereby sustainability assessments are the primary factor in determining whether a particular technology or product’s market entry should be facilitated or impeded. This can be achieved by reducing subsidies for non-sustainable or barely sustainable products, which would simultaneously reduce the barriers blocking innovation and market entry for sustainable technologies and products. In addition, the introduction of eco-design standards will enable the creation of a measurement and evaluation system for ecosystem services. Furthermore, it is necessary to resolve the question of how such a system will be organized, to enable the valorization of business models for ecosystem services for industry and society.

In the medium term, appropriate metrics for assessing sustainability must be continuously improved and the regulatory framework must be adjusted accordingly. Committees for developing regulations at both national and international levels need to be further expanded and staffed with experts in the relevant fields. One example from the regulatory domain concerns the approval process for alternative protein sources for food.

In addition, sustainability assessment criteria should be given greater weight in calls for funding applications. These calls should include a mandatory requirement that the projects submitted in the applications be designed in such a way that all three dimensions of sustainability - economic, environmental and social factors - are adequately addressed, considered collectively and interlinked so that they work as a whole. The Horizon Europe calls for proposals are a good starting point here. In order to ensure that the funding system is continuously updated, projects should regularly be evaluated to determine the extent to which they are actually achieving their intended sustainability targets, and how any barriers and deficiencies can be reduced in future funding initiatives. In addition, financial support must be extended to cover project management expenses, particularly when it comes to funding projects that involve large consortia with numerous project partners. These types of projects are usually more complex and require higher levels of internal communication. If the research conducted in these projects is to meet the required levels of quality and speed, then the management teams in transdisciplinary consortia must be target- and result-oriented, and be organized into an agile, adaptive, flexible hierarchical structure. This structure will be continuously put to the test and adjusted in accordance with the results and new framework conditions.

Long-term implementation

The resilience of bio-based production systems must be increased, while taking the availability of natural resources into account. When any kind of disruption occurs, resilience can provide a crucial competitive advantage. Solutions must be developed based on foresight and scenario analyses, and long-term changes must be initiated. Currently, many bio-economic approaches are leading to ever more intensive use of biological and ecological resources. This can lead to a loss of resilience, as the vulnerabilities that come with fossil-fuel economies are directly carried over to the new system, instead of being eliminated. The bioeconomy offers a wide range of technologies for tackling new challenges. In order to avert the creation of new risks, it is important to first address the issue of designing bio-based production systems in such a way that they can overcome these challenges. Policy funding should be designed to only support forms of the bioeconomy that are resilient to markets changes and will not create new environmental vulnerabilities.

Germany is a net importer of raw materials in the field of bioeconomy. The war in Ukraine exemplified that international supply chains are vulnerable, and that previous geopolitical alliances might not be reliable in the long term. As such, we must focus on conducting potential analyses regarding the availability of raw materials and the possibility of establishing global economic policy partnerships to ensure a long-term supply of bio-based raw materials. The supplier countries must be included in these partnerships, which must be supported by appropriate R&D projects and funding programs. The aim is to create and strengthen resilient value chains and to forge strong connections between the areas of biomass production, supply and conversion.

Technologies

Technological development and innovation are fundamental to driving the transformation to a sustainable industry and society. Process innovations that lead to more efficient utilization of raw materials and residues will be a crucial element in making the circular bioeconomy a reality. The aim here must be to develop environmentally and economically viable processes that can quickly be ramped up to an industrial scale, and thus replace existing approaches based on unsustainable, fossil raw materials.

Short-term implementation

When it comes to developing technologies, in light of the current circumstances, a greater emphasis must be placed on developing bio-based products with high value-creation potential and special qualities and functionalities. Currently, bio-based materials only seem to have sufficient market pull if they have additional special properties and improved functionalities that allow them to clearly stand out from fossil materials. One possible way of expanding materials' property profiles is to integrate the functions of biological components (e.g., enzymes). It is also important to establish and drive the advancement of new technologies, i.e. by exploiting the full potential of biological knowledge to develop novel, sustainable products, and finding new ways of promoting sustainable lifestyles. For example, alternative proteins can help provide nutrition without the need for livestock farming, leading to a significant reduction in this sector's ecological footprint. Developments in the field of biological transformation (see chapter "Biological transformation") such as examples of HyBECCS processes could also significantly contribute to climate protection and sustainability. As such, future calls for funding applications must be specifically interdisciplinary and evaluated accordingly.

Due to the limited availability of biogenic raw materials and the primacy of the "Food First" approach, there must be a greater focus on harnessing the resource of residues from agriculture and forestry, industry and private households so they can be used as a source of material and energy. Unavoidable "waste" must be viewed as a raw material that can potentially be used in a circular economy. Technological, organizational and logistical innovations are required here to enable the recycling of what was previously considered low-grade "waste" of varying quality and availability. It is vital that we develop bioeconomic processes that facilitate the exploitation of a wide range of variable residues for use as raw materials in the industrial manufacturing of products such as chemicals, fibers and plastics.

From a circular bioeconomy perspective, CO_2 must be used to a greater extent as a raw material for the synthesis of organic compounds. Harnessing this additional carbon source could mitigate conflicts regarding the use of land and biomass, as well as enabling the recycling of carbon as part of a circular economy and helping minimize green-house gas emissions. Furthermore, there are many known metabolic pathways that organisms can use to convert CO_2 into high-value chemicals with the help of renewable energy sources, beyond the familiar example of photosynthesis. These pathways are a good starting point for developing the necessary (bio)technological processes and bringing them up to industrial scale. There is an urgent need to take action and establish a level playing field across all technologies, opening up opportunities for biotechnological approaches for using CO_2 for industry-related purposes. So far, individual projects have been funded at the level of the EU, Germany and some of the German federal states. There is a need for intensification and bundling of funding as well as community building.

Medium-term implementation

In order to fully exploit biogenic raw materials and residues in the most sustainable manner possible, a high level of funding is needed for research, development and innovation projects that are specifically aimed at linking biomass production, supply and conversion. Some potential focus areas here include increasing the quality of biomass through knowledge-based breeding technologies, developing biotechnologies for industrial applications and establishing small-scale, decentralized biorefineries in rural regions. To initiate these types of projects, networking must also be supported between stakeholders from the areas of agriculture, processing and industrial conversion. For example, this could be done through networking events or by developing and expanding matchmaking databases, technologies and platforms.

In order to place a greater focus on applied research, projects with higher technology readiness levels (research development up to TRL 7) should be provided with funding. In the food sector, it is necessary to support technologies that will make conventional cultivation methods more environmentally friendly, as well as alternative methods such as vertical farming, insect farming and (photo)-bioreactors. Providing new (and where necessary, adaptive) processing and sensor systems for manufacturing safe, high-quality food and developing alternative protein sources is also important. When it comes to the material use of biogenic raw materials or residues and waste materials, this includes, for example, the production of innovative bioplastics with new properties, the design of which already includes future utilization and recycling paths in the product design. In addition, there is an urgent need to focus on manufacturing materials and chemicals that use CO_2 as a raw material and can be obtained through innovative processes, such as a combination of biological catalysts and renewable energy. As a result, there is a need to further develop tailor-made programs and instruments that address the specific needs of each actor along the value chain. This is the only way that we can achieve the necessary translation of knowledge to application and rapid, widespread adoption of measures. This approach could also reduce barriers to innovation and motivate commercial stakeholders to invest in bioeconomic processes. Some technologies and products that already have a high TRL have not yet been implemented at an industrial level; this is often because there is no return on investment expected within the required time frame, due to the external conditions and the situation in the market. In these cases, it is important to improve the framework conditions, as mentioned in section “Framework conditions”.

Long-term implementation

The objective of the circular bioeconomy must be to strive for the circularity of bioeconomic products and to ensure this in the long term. R&D funding must therefore be further increased in this area. When designing products, consideration must be given to efficient, circular use of resources right from the start. This will enable products and the materials they are made from to remain in a utilization cycle for as long as possible. One example of this is the recycling of composite materials into chemical building blocks that can then be used again. To enable products to be reused, their design process should be aimed at facilitating the longest possible service life, easy maintenance and repairability. When it comes to recirculation, it is also important to consider which materials are used: It must be possible to reuse the materials without their quality being diminished, and products should be modular in design. However, it is important to note that the quality of materials decreases each time they are recycled, meaning that infinite recirculation is not possible. In order to establish sustainable, closed loops in which all resource flows originate from reused or renewable materials, there also needs to be an overall reduction in material usage and economic throughput. Until a complete cyclability of bioeconomic products will have been realized, efforts must be made to achieve its widest possible implementation.

Bioeconomy has a wide range of technologies that can be used to increase the resilience of bio-based production systems while respecting planetary boundaries and increasing the resilience of ecosystems. Funding programs that build on models for resilient, bio-based production systems, must be initiated with the specific aim of only supporting research and technology approaches that strengthen economic and ecological resilience.

Translation

With its technologies, processes, products and services, the bioeconomy opens up a wide range of possibilities for tackling global challenges. However, this means that there is an urgent requirement for innovations, and specifically their transfer to application in industry and society. As such, in this transfer process, we must focus on market implementation and earning public acceptance.

Short-term implementation

In order for bioeconomic technologies and products to come into widespread use, there must be societal acceptance of these technologies and their use in industry. It is therefore necessary to enter into more intensive dialogue with the public and promote social discourse. Appropriate formats for communication must be created, and the advantages of bio-based products and processes must be explained to consumers so they can (re)assess these types of products and processes and articulate their desires and requirements. Another key factor in the context of providing information and disseminating knowledge is the fact that societal objectives, such as those concerning the use of land or conflicts around utilization of biomass and residues, must be explained to citizens in a clearly understandable way and be taken into consideration when it comes to political, technological and industrial activities. There should be particular focus on the manner in which discourse is conducted, the clarity with which the results of this discourse are formulated to enable implementation, the way in which research, government and industry assimilate the results, as well as the possible avenues to reaching an understanding and resolving conflicts in the bioeconomy field. This can be achieved through (online) dialogues with citizens and transparent information campaigns that are freely available to the general public to inform citizens about bioeconomy developments and targets. One particularly useful method of presenting information to citizens in a more understandable manner is to include examples of best practice in these campaigns.

Medium- to long-term implementation

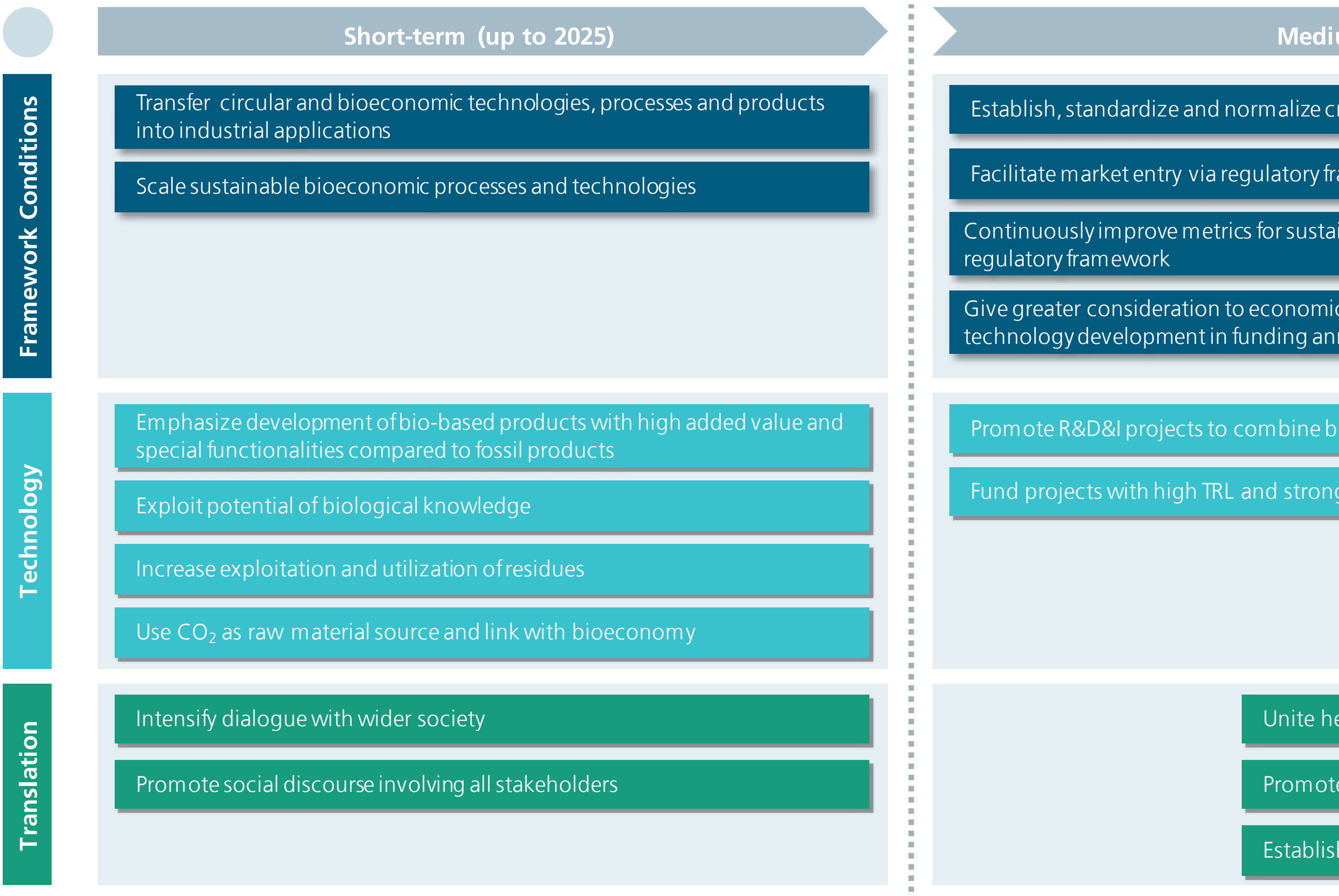
The bioeconomy community has been heterogeneous up until this point; initiatives must be set out to turn the focus of all stakeholders in the community toward common goals and focal points. Attention must be given to determining how to take action on these objectives and which targets need to be addressed. This will require an open culture of innovation and communication between researchers, companies, society and government. Interaction platforms, such as regional competence and transfer centers, are also required to promote interdisciplinary and transdisciplinary dialogue between the scientific and industrial sectors. In terms of policy, it should be noted that the different areas of the bioeconomy mean that many European and national institutions dealing with agricultural, forestry, economic, research, energy and environmental policy are involved in decision-making. As these institutions sometimes represent different political interests and prioritize

different topics, guiding principles and objectives can vary within the bioeconomy. The goal must be to formulate coordinated and coherent bioeconomy policies, including in relation to providing land for biomass use. To achieve this, cross-departmental and cross-level political decisions must be made and communicated. An example for this is the interministerial working group on bioeconomy (Interministerielle Arbeitsgruppe zur Bioökonomie) already established in Germany; similar approaches must be encouraged at the European as well as at regional level and between the European Commission, the member states and the regions.

Industrial model ecosystems and the establishment of value creation networks must be promoted across the EU. Consideration needs to be given to where centralized biorefineries provide added value and where decentralized, regional biorefineries are preferable (particularly considering the products' potential buyers from the chemical industry and other chemical pilot plants). The exchange of expertise within and between regional initiatives and different model regions must continue, as in eco-model regions and bioenergy villages, for example. This is because past experiences have shown that this exchange motivates local stakeholders to create shared visions for regional development. Such initiatives also help to achieve a high level of identification with the relevant goal among citizens. The existing model projects in bioeconomy must therefore be advanced as a matter of priority, their success factors must be surveyed, and they must be supplemented with other regional projects in this general area. In addition, methods for the wider public to engage in dialogue and participate should be implemented as integral elements of regional model projects.

In the area of education and training, appropriate priorities must be set for the development of universities and colleges. Bioeconomy must be more strongly integrated into education and training beyond programs in individual universities.

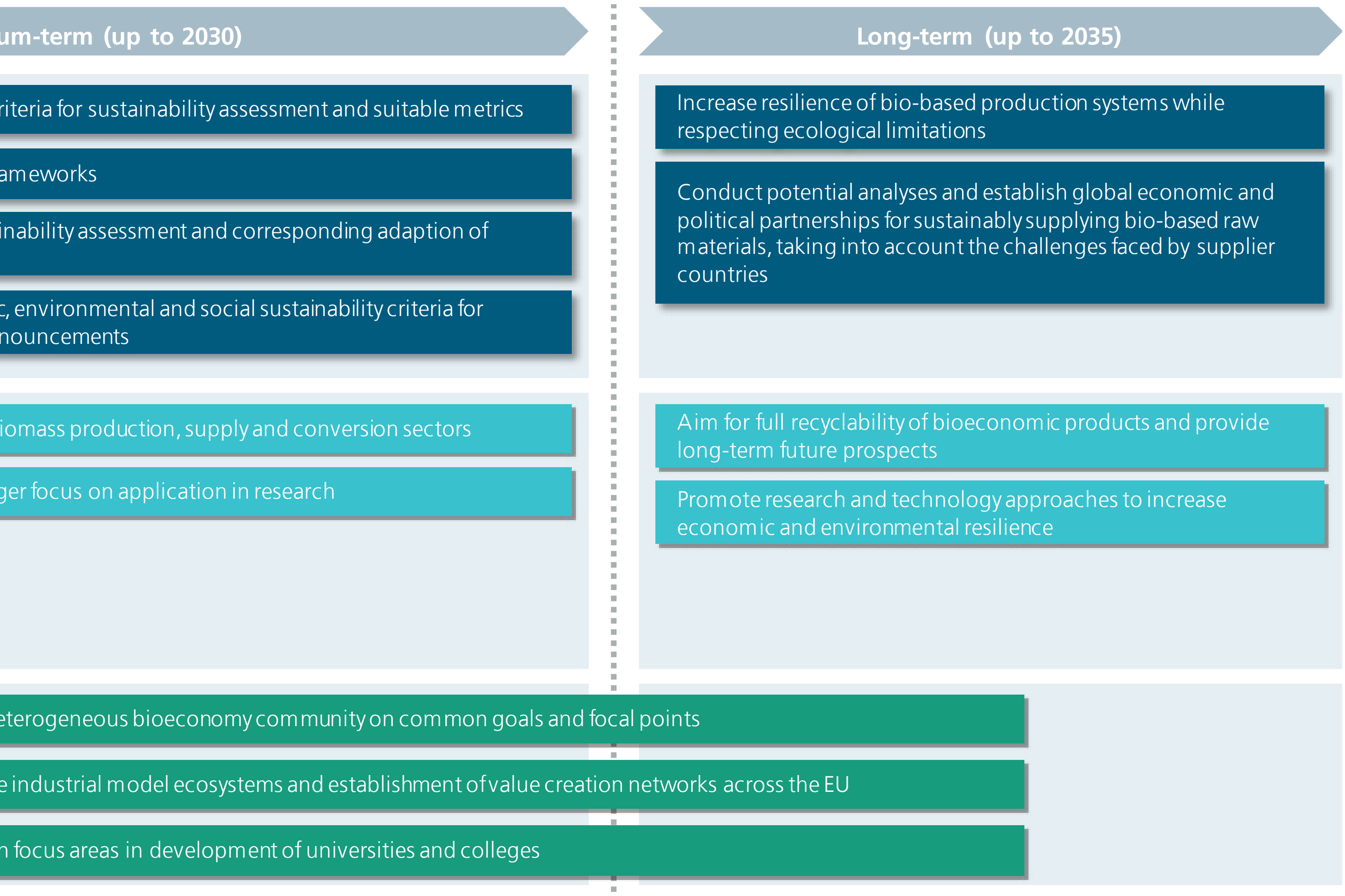
Fig. 6 Overview recommendations of action



	Short-term (up to 2025)	Medi
Framework Conditions	Transfer circular and bioeconomic technologies, processes and products into industrial applications Scale sustainable bioeconomic processes and technologies	Establish, standardize and normalize c Facilitate market entry via regulatory fr Continuously improve metrics for sustai regulatory framework Give greater consideration to economic technology development in funding an
Technology	Emphasize development of bio-based products with high added value and special functionalities compared to fossil products Exploit potential of biological knowledge Increase exploitation and utilization of residues Use CO_2 as raw material source and link with bioeconomy	Promote R&D&I projects to combine b Fund projects with high TRL and stron
Translation	Intensify dialogue with wider society Promote social discourse involving all stakeholders	Unite he Promot Establis

According to a 2022 survey by the European Commission, by 2030, there will be increased demand for people with higher-level qualifications in fields relating to the bioeconomy (including the food industry, forestry, chemistry and chemical technology, micro- and biotechnology, material sciences and production). Digital and industrial technologies, business models and socioeconomic developments will all influence the skills required here. Some possible focus areas therefore include systems thinking, technological and digital expertise, and the inclusion of ethical aspects in the use of biological resources. It is recommended that transdisciplinary curricula are developed in order to build connections between the different bioeconomy focus areas. This applies to the technologies that were addressed in chapter "Applications and opportunities for the bioeconomy," i.e., technologies in the areas of sustainable alternatives to fossil materials, closed-loop recycling and value creation from residual flows. In order to meet the demand for qualified employees, there must be better collaboration between institutes of higher education, industry, government and stakeholders from civil society. The advantages of the bioeconomy can be highlighted by initiatives for raising awareness and by integrating the bioeconomy into career guidance structures for young people and adults. In addition, establishing long-term mandatory training responsibilities within bioeconomy strategies will help strengthen initiatives for building related skills.

Fig. 6 shows a summary of all the recommendations given for the three subject areas discussed.



um-term (up to 2030)

riteria for sustainability assessment and suitable metrics

ameworks

inability assessment and corresponding adaption of

c, environmental and social sustainability criteria for nouncements

iomass production, supply and conversion sectors

ger focus on application in research

Long-term (up to 2035)

Increase resilience of bio-based production systems while respecting ecological limitations

Conduct potential analyses and establish global economic and political partnerships for sustainably supplying bio-based raw materials, taking into account the challenges faced by supplier countries

Aim for full recyclability of bioeconomic products and provide long-term future prospects

Promote research and technology approaches to increase economic and environmental resilience

eterogeneous bioeconomy community on common goals and focal points

e industrial model ecosystems and establishment of value creation networks across the EU

n focus areas in development of universities and colleges

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