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Exploring Innovative Technology Fields for a Circular Bio-Based Economy

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Hinweise

Das diesem Bericht zugrundeliegende Vorhaben wurde mit Mitteln des Bundesministeriums für Bildung und Forschung unter dem Förderkennzeichen 031B0783 gefördert. Die Verantwortung für den Inhalt dieser Veröffentlichung liegt bei den Autorinnen und Autoren.

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Executive Summary

The report provides an overview of the assessment of the 12 technology fields in regard to explore the potential development, transformative nature, and impact of bio-based innovations on further deployment of bioeconomy. This assessment reveals a diverse range of innovations driving the bioeconomy. From alternative proteins and carbon capture and use to biopharmaceuticals and innovative wood products, each technology field presents unique opportunities and challenges. The innovations vary in their disruptiveness, dominant type of innovation, economic relevance, and potential ecological and social impacts. The report explored different typologies of innovations in the bioeconomy and their connection to sustainable development goals.

The assessment highlights the disruptive potential of various technology fields, with some innovations having the capacity to transform entire value chains and industries. While certain technologies offer gradual advances and efficiency gains, others have the potential to create entirely new markets and business opportunities. Identifying pivotal technology fields and understanding their disruptive nature is crucial to capture the trends and developments in the bioeconomy.

Projected economic impacts of bio-based innovations indicate promising growth prospects for the bioeconomy. However, the ecological and social implications of the technology field are not clear-cut and uncertain. While considering the single technology fields there is various potential for environmental impacts, e.g. via higher resource efficiency, less CO_2 emissions compared to fossil-based products. However, considering the limitations of availability of biomass, broad diffusion of such innovations may lead to a further increase and further industrialization of land uses as well of potential risks of such technologies. Therefore, it is critical that the transition to bio-based solutions must align with environmental goals. Additionally, the social implications of bioeconomy technologies on health and well-being must be carefully considered to ensure equitable and inclusive development. Balancing economic growth with environmental sustainability is a key challenge for the deployment of bio-based innovations.

The report suggests in-depth case studies for four technology fields: meat alternatives, AI in agri-food systems, biopharmaceuticals, and second generation bio-based surfactants. These forthcoming case studies aim provide detailed insights to potential future trajectories and the economic, ecological, and social impacts of these innovations, hence they aim to contribute to a comprehensive understanding of the bioeconomy's potential role in sustainable development.

By leveraging key enabling technologies, fostering innovation, and promoting sustainable practices, the bioeconomy can play a central role in achieving global sustainability goals. Policymakers, researchers, and stakeholders may collaborate to seize the opportunities presented by the bioeconomy and work towards a more prosperous and environmentally responsible future for all. The findings from this report provide a foundation for deeper understanding of innovation processes and informed decision-making and policy formulation, guiding the way towards a greener and more resilient bio-based future.

1 Introduction

The bioeconomy represents a pivotal paradigm shift towards sustainability and circularity, where biological resources are harnessed to produce goods, energy, and services. Embracing the potential of biotechnological innovations, the bioeconomy seeks to transform industries and societies by reducing reliance on finite fossil resources and mitigating environmental impacts. As nations strive to foster a sustainable and resilient future, understanding the dynamics of technological innovations within the bioeconomy becomes crucial. This assessment delves into the exploration of various technology fields, their potential developments, and the potential impacts they may have on the bioeconomy.

The concept of the bioeconomy emerged as a response to the escalating challenges posed by climate change, resource depletion, and environmental degradation. Recognizing the need for a more resilient and inclusive economic model, policymakers and researchers turned to biological resources as a viable alternative to conventional fossil-based industries. The bioeconomy encompasses a wide array of sectors, including agriculture, forestry, biotechnology, and bioprocessing, where biologically derived resources are transformed into value-added products and services.

Through technological advancements, the bioeconomy aims to optimize resource efficiency, foster innovation, and pave the way towards a greener and more sustainable future. By harnessing the potential of biotechnologies, such as optimizing enzymes, synthetic biology, and fermentation processes, the bioeconomy endeavors to develop bio-based alternatives to traditional products, including fuels, chemicals, and materials.

1.1 Purpose and Scope of the Assessment

The primary goal of this assessment is not to rank or benchmark technology fields but rather to explore their potential development, disruptive nature, and economic, ecological, and social impacts within the context of the bioeconomy. Understanding the dynamics and potential implications of technological innovations is essential for steering the bioeconomy towards a sustainable and circular pathway as envisioned by the National Bioeconomy Strategy.

The assessment takes a two-stage approach. Firstly, a screening and preliminary evaluation of selected technology fields will be conducted to gauge their innovativeness, potential development, and overall impact on the bioeconomy. Secondly, based on these insights, four case studies will be identified, focusing on dynamic technology-driven fields and sectors. These case studies aim to provide specific insights in the future development paths, the potential impact and to provide partly contributions to measurement by indicators or input to modelling approaches in this monitoring project.

1.2 Selected Technology Fields

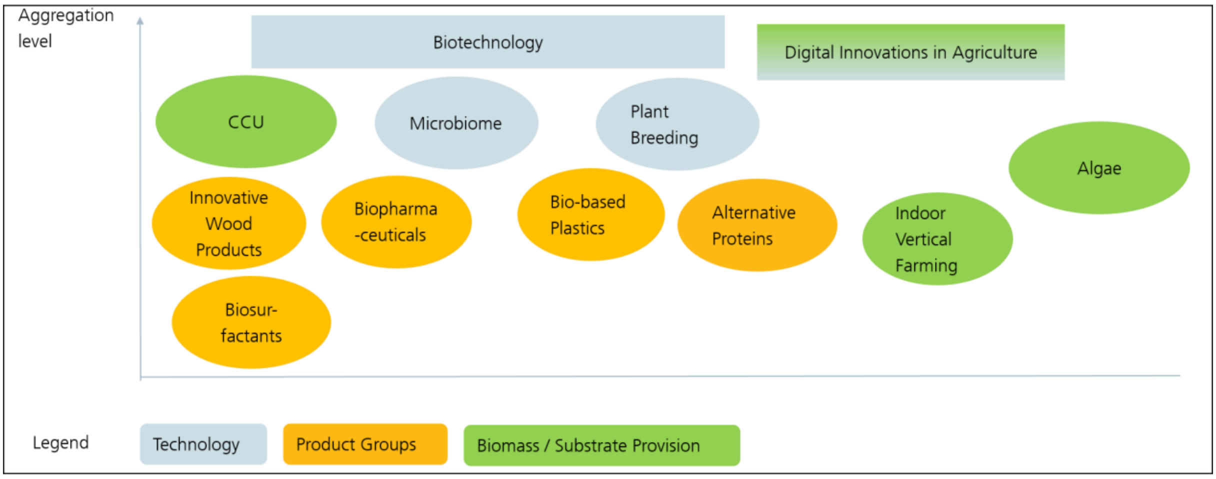
The assessment encompasses twelve distinct technology fields, each contributing to the diverse landscape of the bioeconomy. These technology fields were selected based on their level of innovativeness, potential for significant change in various applications, and economic and ecological relevance. The fields cover a broad range of innovations, including technologies, biomass provision, and product groups, ensuring a comprehensive evaluation of the potential innovations within the bioeconomy. Additionally, to ensure a comprehensive analysis, technology fields were chosen from different levels of aggregation, encompassing various types of innovations, such as technologies, biomass provision, and product groups.

The twelve technology fields include:

- Carbon Capture and Use (CCU)
- Alternative Proteins
- Biopharmaceuticals
- Innovative Wood Products
- Bio-based Plastics
- Bio-based Surfactants
- Agriculture 4.0
- Indoor Vertical Farming
- Algae
- Plant Breeding
- Biotechnology
- Microbiome

The Figure 1 below indicates the aggregation level of the technology fields. The colour indicates, whether the field addresses a concrete technology (blue) or different technologies that address either biomass / substrate provision (green) or application product groups (orange).

Figure 1: Characterization of technology fields



Source: Fraunhofer ISI

Each technology field will undergo thorough assessment, providing insights into its definition, key trends, developments, drivers, barriers, publication, and patent analysis, market relevance, and potential economic, ecological, and social impact on the bioeconomy. By conducting such anaylsis, we aim to gain a holistic understanding of the transformative potential of these technologies and their role in shaping the sustainable bioeconomy of the future.

While all fields have been analysed in a similar manner, some limitations exist. As they are intentionally not defined on the same aggregation level / level of granularity precise information and clarity about the impacts is different, as those fields on a broader aggregation level contain heterogeneous products and processes.

Moreover the information availability is different between the fields. While limitations exist for all, for some tech fields there exist detailed critical assessments of market evolution and outlook, while for others only some key numbers from commercial case studies exist, which do not provide a publicly available, transparent delineation of the market. Moreover, they are often very optimistic.

Moreover it is important to note that the assessment does not aim to benchmark or rank the technology fields, but rather to explore their potential development, disruptive nature, and economic, ecological, and social impacts on the bioeconomy. The results highlight the differences and potential implications of each technology field on the bioeconomy's future trajectory.

Furthermore, we acknowledge that quantitative, reliable information on potential impacts of the innovations is often scarce and dispersed. Proponents claim high sustainability potential, while critics express concerns about potential detrimental effects on the environment and land use. While we aim to incorporate critical views in the discussion of individual technology fields, it is beyond the scope of this assessment to address all macro-level implications of each technology case.

2 Methodology

2.1 Characteristics of Innovations and technology fields in the bioeconomy

As already indicated the innovations in the bioeconomy differ significantly from each other, in particular regarding the following dimensions:

- **Type of innovation**: A typical distinction in innovation literature is made between process innovations vs. product innovations. Process innovations refer to improvements in the methods and techniques used to produce goods or services, while product innovations refer to the creation of new or improved products that meet specific market demands and address consumer needs.. Process innovations may lead more to productivity effects and maybe price reductions or rationalization, product innovations may lead to new markets and business opportunities.
- **Type of impact:** The innovations in the bioeconomy may have quite different goals focussing to different degrees on economic, ecologic, health or other social dimensions. Moreover also in economic terms the contribution could highly differ e.g. from productivity gains e.g in primary processing versus securing or adding value added and high-skilled employment in the country. Consequently, the range of expected main impacts is large and differs between innovations, e.g. substitution of resource basis, increasing primary production productivity, reducing land use, increasing sustainability of production, new product groups with quality improvements (e.g. better health/higher sustainability), new high-value added value chains.
- **Disruptiveness**: While (usually incremental) innovations and technology fields only substitute fossil-based products and process with a similar performance, while the rest of the value chain remain rather unchanged, other innovations may lead to broader changes of the product (e.g. specific characteristics …) and value chain “disruptions”.
- **Relevant sector(s):** Some innovations mainly effect the primary product (e.g. ICT in agriculture, algae innovation), while others lead to changes in activities of conversion sectors (e.g. bio-based surfactants, microbiome). These conversion sector also differ greatly from each other, e.g. regarding whether bulk products or niche products are produced, new products innovations vs. process innovations are relevant, etc.

There have been a few attempts to elaborate typologies of innovations in the bioeconomy, which provide valuable insights in categorization, but they address each only one dimension.

Bröring et al (2021) differentiate between four types of the bioeconomy, namely new products, new processes, substitutes and organizational innovation. These types differ in their degree of innovation and whether they are focused on product, process or organizational innovation. Moreover, this is mainly applicable for concrete products and process and less for broader technology fields considered here.

Stark et al. (2022) focus on the outcomes of innovations and differentiate four distinct pathways, through which bio-based transformation can generate positive or negative outcomes in multiple domains of the Sustainable Development Goals. They differentiate between „Increases in biomass use efficiency and new biomass uses[1]", „Substitution of fossil- by bio-based resources", „Increases in primary sector productivity", "Bio-based value added in low-volume/ high-value industries". This approach supports to analyse potential impact of bio-based innovation, however that attribution of innovations to a certain pathway in advance is not always unique and not easy to determine for the future.

Still, these categorization help to visualize the broad spectrum of innovations in the bioeconomy and the differences between them. The categories of these typologies are combined with the dimensions of disruptiveness and relevant sectors in the finding table 17 in section 15.

2.2 Sources

The methodology employed for this assessment involves gathering information from diverse and reliable sources to ensure comprehensive and accurate insights into the technology fields under examination. The data collection process involves the literature review and analysis of various databases. The following data sources have been utilized:

- Scientific Literature Review: A review of key academic papers, research articles, and reports related to the technology fields was conducted. This literature review provided valuable information on innovations, developments, and potential impacts of each technology field.
- Patent and Publication Databases: we elaborated publication and patent indicators to assess the scientific dynamics (Publications) and technological (patents) global dynamics as well as the current competitiveness of Germany in these areas. Therefore we developed for each technology field rather broad delineations of the technology field for Scopus (publications) and STN (patents).
- Market Studies and reports: Accessing commercial case studies provided valuable data on market evolution, industry outlook, and the adoption of bio-based innovations in various sectors.

2.3 Technology Field Analysis

Based on a respective definition and delineation analysis of the each technology field contain the following content:

- **Current status and potential future developments** : description of the evolution and future prospects of the technology fields, including potential barriers and drivers for market adoption..

[1] Please note that in this pathway it is undefined whether the overall biomass production and use increases or not. While new biomass use may likely imply rising biomass demand, higher biomass use efficiency may lead to less demand, depending on potential rebound effects.

- **Publication and Patent Analysis**: Analysing the number of publications and patents related to each technology field to gauge the development of research and development activities and technological competitiveness of Germany.
- **Market Outlook**: Understanding the current market size, trends, including position of Germany
- **Economic, Ecological and Social Relevance**: Evaluating the significance of the technology field in terms of its potential economic growth, social aspects, and contribution to resource efficiency and environmental sustainability.
- **Suitability for case study**: The suitability if the technology field for an in-depth case study is discussed by considering the criteria below

2.4 Case-study selection

Based on the technology field assessment we select four case studies from the technology field assessments for in-depth analysis in order to better understand the potential impact to the bioeconomy and also to explore potentially approaches to measurement and potential connection to the modelling in Symobio 2.0.

The key criteria for selection are:

Relevance: The technology field should relate to high disruptiveness and/ or significant prospective economic and ecologic relevance* of the technology field (not necessarily only positive expected impacts)

Suitability for Analysis: There should be some information material available for closer in-depth assessment. Moreover, the case should be suited to investigate additional relevant research questions either qualitatively or quantitatively. Regarding the later either elaborations of economic and innovation indicators or potential input and context-setting to scenario modelling in other WPs is desirable to achieve (e.g. estimation of bio-based, share, productivity changes, lessons-Learned to combine case studies and modelling).

In addition to these two criteria, the portfolio of selected case studies should cover different types of innovation/solutions to different challenges and both qualitative and quantitative assessments.

3 Technology Field Bio-Based Surfactants

3.1 Characterization of Technology Field

3.1.1 Definition and Delineation

According to European CEN standards[2] a bio-based surfactant is "a surface-active compound that is wholly or partly derived from biomass produced either by chemical or biotechnological processing". They are mostly derived from oils and fats or from sugar. Bio-based surfactants are applied as specialty chemicals and can be included in household detergents, personal care products, agricultural chemicals, oilfield chemicals, industrial cleaning, and others (Ismail et al. 2022).

3.1.2 Current status and potential future developments

Bio-based surfactants are already commercially available in a wide range of industries for many years. They achieve a slightly higher market growth than the overall market of surfactants (see 1.3). Most of the bio-based surfactants are usually produced by chemical synthesis but integrate fats, sugars or amino acids obtained from renewable sources. However, a key recent development is the high focus of R&D&I activities on the so-called 2nd generation of bio-based surfactants, namely microbial bio-based surfactants (e.g. rhamnolipids, sophorolipids, surfactin). They are fermentation-based and comprise promising types of surfactants. They are made from different feedstocks, e.g. sugars but also from food waste are currently under development.[3] Most of them are not yet on the market (Mulligan 2021; Farias et al. 2021). They bear the potential to expand the present range of applications and industrial sectors of biosurfactants significantly. This is due to their higher structural diversity and the possibility to generate novel and application-tailored functionality (e.g. antimicrobial or antiviral effects, but also better biodegradability).

For bio-based surfactants in general, but especially for commercialization of microbial bio-based surfactants, in particular, the following key drivers and hurdles arise (Table 1).

Table 1: Drivers and barriers for bio-based surfactants

Drivers	Barriers
Growing consumer preference and increasingly stringent regulatory requirements for eco-friendly alternatives to conventional surfactants	**High prices of bio-based surfactants**[4]
Alternative bio-based feedstock products increase supply portfolio enables application firm to diversify their resource suppliers	Technical challenges to increase cost competitiveness or higher value added, among them improving microbial production strains to generate additional biosurfactant functionalities, optimisation of production processes to increase productivity and yields, and broadening

[2] CEN/TR 17557:2020(MAIN): Surface active agents - Bio-based surfactants - Overview on bio-based surfactants

[3] https://cen.acs.org/business/specialty-chemicals/Switching-sustainable-surfactants/100/i15

[4] While the average price of some synthetic surfactants are estimated to one to four dollars per kilogram, the average price of sophorolipids (microbial biosurfactants), is estimated as high as $ 34 per kilogram (Ismail et al. 2022; Farias et al. 2021).

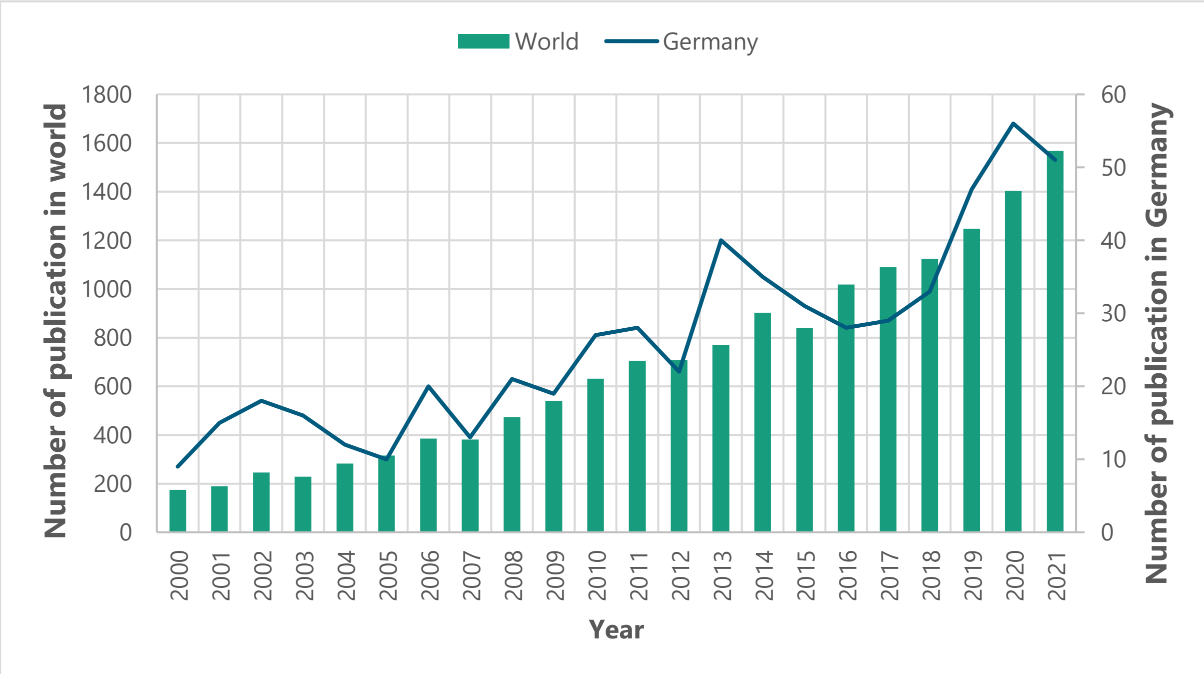
	the fermentation substrate portfolio (e.g. waste, lignin, algae)
Many large chemical firms are active in the field of bio-based surfactants which have high commercial credibility and are able to scale up production to lower costs	The dependency of bio-based surfactants demand on the volatility and economic downturn of various downstream end-user industries

Source: (Ismail et al. 2022; Müller 2021)

3.2 Publications and Patents

The publication analysis for the whole field of bio-based surfactants shows a continuous rise over time world-wide. In Germany the development is less dynamic and Germany's share of world wide publications has fallen from around 7-8% in the early 2000s to around 3-4 % in the early 2020s.

Figure 2: Publications for bio-based surfactants 2000-2021

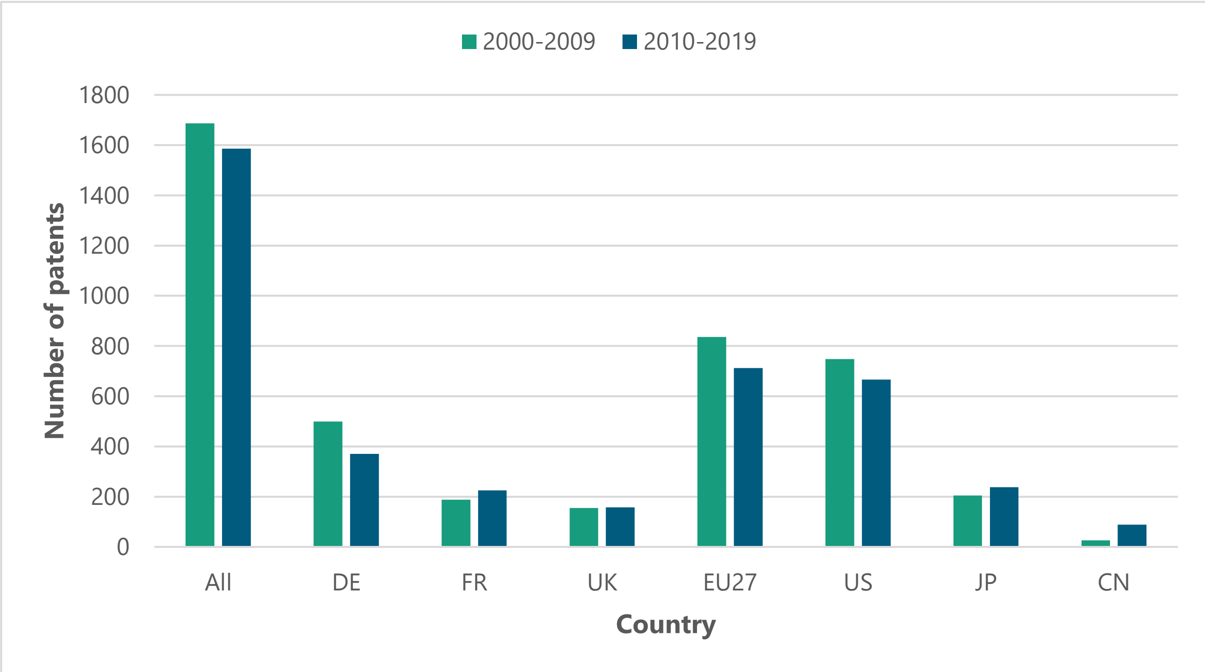


Source: Fraunhofer ISI based on Scopus

Regarding to patents, the overall evolution is rather stable with a slightly lower number of patents in 2010-2019 compared to 2000-2009. The EU-27 is in total slightly ahead of the US in patenting, with Germany generating around the half of the EU patents. Japan and China register more patents in the more recent time period, but are behind the Western regions.

Additional patent analysis (graphs not shown) for the three most relevant product types of microbial biosurfactants (rhamnolipid, sophorolipid, surfactin) show an almost identical pattern on dynamics and country distribution, with the only difference that the US is slightly ahead of the EU.

Figure 3: Transnational patents for biosurfactants, comparison of 2000-2009 and 2010-2019



Source: Fraunhofer ISI based on STN

3.3 Market Outlook

Bio-based surfactants are expected to have significant market potential. According to Spekreijse et al. (2019) surfactants are the chemical product category with the highest diffusion of bio-based products. The share of bio-based surfactants of all surfactants is estimated to around 50%. Around 1,500 kt/a bio-based surfactants are currently produced in the EU, they present roughly 30% of the total production volume of bio-based chemicals. The European market presents 40% of the global bio-based surfactants market. The expected growth rates for bio-based surfactants are relatively high (4% p.a.) compared to other biochemical markets with 2% p.a. until 2025. Some market forecasts[5] are even higher (around 6% p.a.). Today, the global market for microbial biosurfactants is negligible compared to both, the conventional surfactant and the bio-based surfactant market (Müller 2021). However, this segment is expected to gain importance in the future. According to Müller (2021) the „most promising target markets [for bio-based surfactants] are those where bio-based surfactants can be sold at a higher price such as the personal care and cosmetics sector and, more specifically, the niche markets of natural and eco-friendly cosmetics."

Germany has strong players in the market of bio-based surfactants and leads the production in the EU (Spekreijse et al. 2019). There are close strategic links between the bio-based surfactant providers (Evonik[6], BASF) and the users (Unilever, Henkel[7]). Moreover, some of these firms as well as im-

[5] https://www.mordorintelligence.com/industry-reports/biosurfactants-market; https://www.marketresearchfuture.com/reports/bio-based-surfactants-market-3907; https://www.verifiedmarketresearch.com/product/bio-surfactants-market/

[6] In January 2022 Evonik announced to build world's first industrial-scale production plant for rhamnolipids (microbial biosurfactants) and will invest a three-digit million-euro sum in the construction of a new production plant in Slovakia. Evonik's rhamnolipids will provide Unilever with foam-forming properties and high-performance cleaning results and with the environmental benefits of being fully based on natural sugars and 100% biodegradable.

[7] Henkel signed a deal with BASF, which will deliver 110,000 t per year of ingredients for Henkel in Europe manufactured with renewable feedstocks on a mass-balance basis (https://cen.acs.org/business/specialty-chemicals/Switching-sustainable-surfactants/100/i15. These ingredients will be partly used for bio-based surfactants.

portant R&D institutions participate in the Alliance Biosurfactants. The overarching goal of the alliance is to find sustainable and scalable alternatives to chemically synthesized surfactants from fossil raw materials.

3.4 Potential Impact

Surfactants present only around 2% of the overall chemical production and half of it is already bio-based (Spekreijse et al. 2019). Hence, any impact of bio-based surfactants discussed below is limited in magnitude as the additional volume of bio-based surfactants is low. The potential contributions apply not necessarily only but in particular for microbial biosurfactants.

Economic contribution

Economically, bio-based surfactants present one of several rather high-value added markets. The use of innovative technology and prospectively alternative feedstock resources together with strong application sectors present favourable conditions to secure Germany's strong competitiveness.

In addition, the potential market uptake of microbial biosurfactants may present an opportunity to reduce the dependency on imports, which is currently high, as e.g. around 2/3 of the feedstocks used for EU production of bio-based surfactants are imported from non-EU countries (Spekreijse et al. 2019).

Ecological contribution

Considering ecological effects, many authors claim a general ecologic advantage of bio-based surfactants,, due to the use of natural resources, their low ecotoxicity, and high biodegradability. However, Briem et al. (2022) point out ".. they are not standalone indicators for sustainable products, but rather input parameters for a comprehensive sustainability assessment." However there is only limited more holistic information available on the environmental performance of bio-based surfactants. E.g. Briem et al. (2022) found only six reliable LCAs for their meta-study on bio-based surfactants, only two of them referring to microbial bio-based surfactants.

Potential advantages also derive from lower CO_2-emissions from the mild conditions of fermentation, which is carried out at ambient temperature and pressure. This may lead to lower energy requirements. However, as for bio-based products in general, as the feedstocks for bio-based surfactants today are sugars and oils, agricultural practices have a huge impact on sustainability and impact of bio-based surfactants is disputed, in particular in the case of palm-oil derived products (. While the above mentioned detailed LCAs have not been subject of this technology profile, it can be stated that such LCAs usually do not cover land used changes that are specially relevant for the use of oils imported from third countries. Those effects may dominate the overall sustainability effects of bio-based surfactants

3.5 Summary of relevance and suitability for case study selection

Bio-based surfactants present a flagship product group and a success stories in terms of market relevance for bio-based chemicals. On the one hand the adoption in the chemical industry is already high and on the other hand there are significant innovation activities on advanced biotechnological products with innovative product performance that will likely be commercialized in the coming years. Moreover, while sustainability contributions are open per se as for many bio-based products, biodegradability, non-toxicity and energy savings may lead to potential advantages. However, bio-based surfactants will even in optimistic perspective remain a niche and will not directly lead to highly significant positive economic and ecological effects.

A potential case study may focus on microbial bio-based surfactants to study more in-depth the innovation dynamics over time (e.g. by more detailed patent and publication analysis) and could highlight in which concrete applications new bio-based innovations are used or will probably be used in the near future. Moreover, it could be investigated to which PRODCOM groups these microbial bio-based surfactants belong and whether production volume could be estimated and continuously measured. Moreover, it could be analyzed, which role the German location could play, as today Germany is the EU leader in bio-based surfactants. However, as the volume of bio-based surfactants is limited, a case study would hardly serve to provide input for modelling on a sectoral level. Moreover, additional economic indicators (e.g. economic characteristics of companies, value added) will be difficult to be capture on a firm level, as surfactants are to a significant part produced by large companies, which have a significant set of other bio-based and fossil-based products in their portfolio. Hence, the separation of their bio-based surfactants activities from their other activities and consequently bottom-up firm estimations of any economic indicators is hardly possible.

4 Technology Field Bio-Based Plastics

4.1 Characterization of Technology Field

4.1.1 Definition and Delineation

While there are different definitions of bio-based plastics, here it is used for plastics, which are – at least in part – produced from renewable biomass as a feedstock. They may be biodegradable or durable (FNR 2019).

4.1.2 Current status and potential future developments

Bio-based plastics have already a long history and have been used in niche applications for a long time. There many different types of bio-based plastics and different feedstocks used (e.g. oil, lignin, starch, protein, rubber, etc.). There are intensive R&D&I efforts for developing further new bio-plastic products (e.g. PEF[8]) and applying innovations in production processes to reduce cost and decrease environmental impacts[9].

Two types of bio-based plastics can be distinguished: Drop-ins and non-drop-ins. Drop-ins have identical or similar technical properties as their fossil counterparts. Drop-ins do not face high market uncertainties, can partly build on existing infrastructure and existing technological knowledge for the conventional product and do not lead to switching costs for users. However, competition against the fossil-based products with similar performance is mostly reduced to relative price. Non-drop-ins (e.g. PLA, PHA)[10] differ in their performance to fossil-based counterparts and provide new functionalities, but may also have technical disadvantages and/or are not suitable yet for all desired application areas. More recently, market outlooks[11] put a focus on the biodegradability of a product, and distinguish between biodegradable versus non-biodegradable bioplastics. The contribution of bioplastics to a circular bioeconomy are intensively discussed and influenced by technical properties of the products and recycling technologies, but also framework conditions (availability of infrastructures for collection, separation from other waste and recycling of bio-based plastics).

Important innovations are also dedicated to the type of feedstock used: 2nd generation bio-based plastics are produced from non-food feedstocks, such as lignocellulosic biomass and cooking oils and fat waste (Vandenberghe et al. 2021). Still in the R&D phase are 3rd generation bio-based plastics which are produced from sugars or oils produced by micro-organisms (microalgae, bacteria, mushrooms, yeasts and others) or from municipal waste material. A recent analysis by the Nova Institute claims that non-food feedstocks already have a high share (58 %) in the world-wide production of bio-based plastics[12]: The major feedstock used for bio-based polymer production is glycerol (37 %), as a biogenic process by-product from biodiesel production. This glycerol is mainly used for epoxy resin production via epichlorohydrin as an intermediate. Moreover, 9 % of bio-based plastics feedstocks come from cellulose (mainly used for cellulose acetate). In addition, 12 % of the biomass are from non-edible plant oil, such as castor oil and 2 % from edible plant oil. Hence, also some of the non-food feedstock used depends on cropland as e.g. the high dependency on biodiesel shows. Food feedstock based bioplastics come from starch (24%) and sugars (16%).

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[8] Polyethylene Furanoate

[9] https://www.european-bioplastics.org/market/

[10] Polylactic acid and Polyhydroxyalkanoates

[11] https://www.european-bioplastics.org/market/

[12] http://nova-institute.eu/press/?id=237

For bio-based plastics, the following key drivers and hurdles arise (Table 2). As a general issue the uptake of bio-based products will depend on policy incentives, as without further support the disadvantages of higher costs and learning and scale effect disadvantages of bio-based plastics can hardly be compensated. However, the policy framework conditions for bio-based plastics are not very favourable in Germany as well as many other countries, probably because for some of them their contribution to sustainability is doubted (Rosenboom et al. 2022; Umweltbundesamt 2017; Wydra et al. 2021)..

Table 2: Drivers and barriers for bio-based plastics

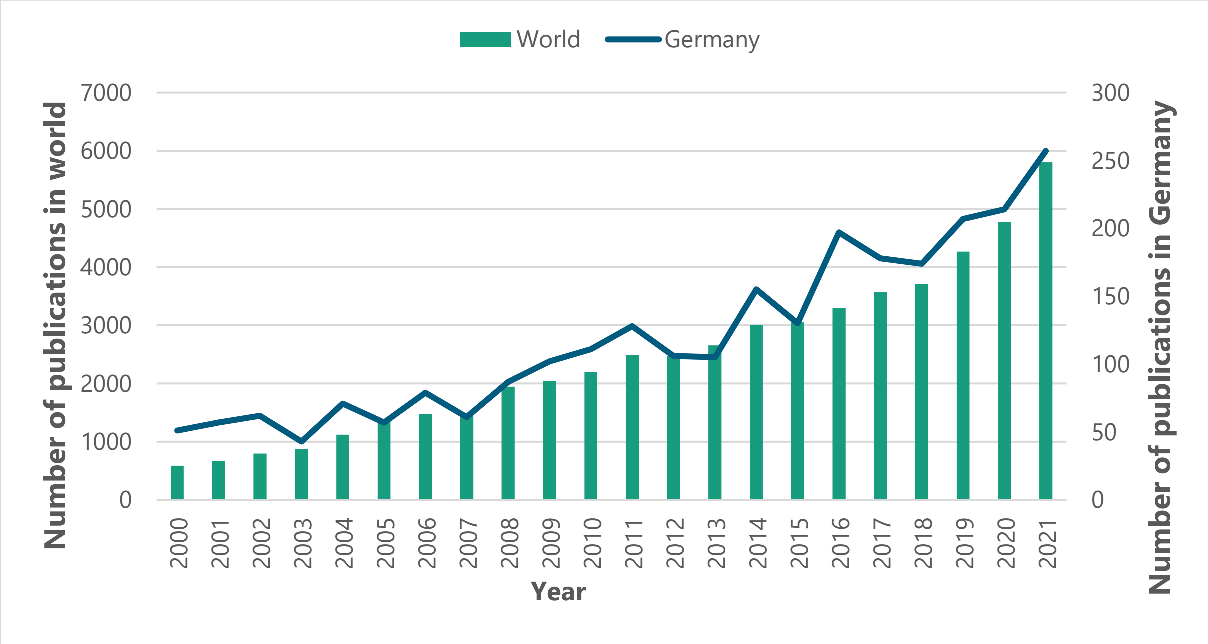
Drivers	Barriers
Non-drop ins bio-based plastics provide additional functionalities	Technological challenges, e.g. delivering constant plastics quality despite fluctuating feedstock quality, making production organisms more robust and productive under production conditions, avoiding undesired plastic properties (e.g. smell, colour), development of new recycling technologies
High pressure to substitute fossil-based plastics	High costs for bio-based plastics
Interest by large brand-owners	no specific policy incentives for bio-based plastic sin Germany
High diversity of bio-based plastics developed and partly progress in cost competitiveness achieved	Very critical discussions about sustainability performance of bio-based plastics and potential contribution of bioplastics to societal challenges (e.g. littering problem: Microplastics as argument against any type of plastics)
	Lacking end-of-life options, no adequate infrastructure for bio-plastics recycling

Source: (Panchaksharam et al. 2019; Wydra et al. 2021b; FNR 2019)

4.2 Publications and Patents

Figure 1 shows the results of a publication analysis for the entire field of bio-based plastics. It indicates an ongoing growth in publications from 2000 to 2021, whereas there was a higher increase in the last 3 years. The same trend relatively applies for Germany. However, Germany's share of world wide publications was 8-9% from 2000-2002 and since then just between 4 and 6%.

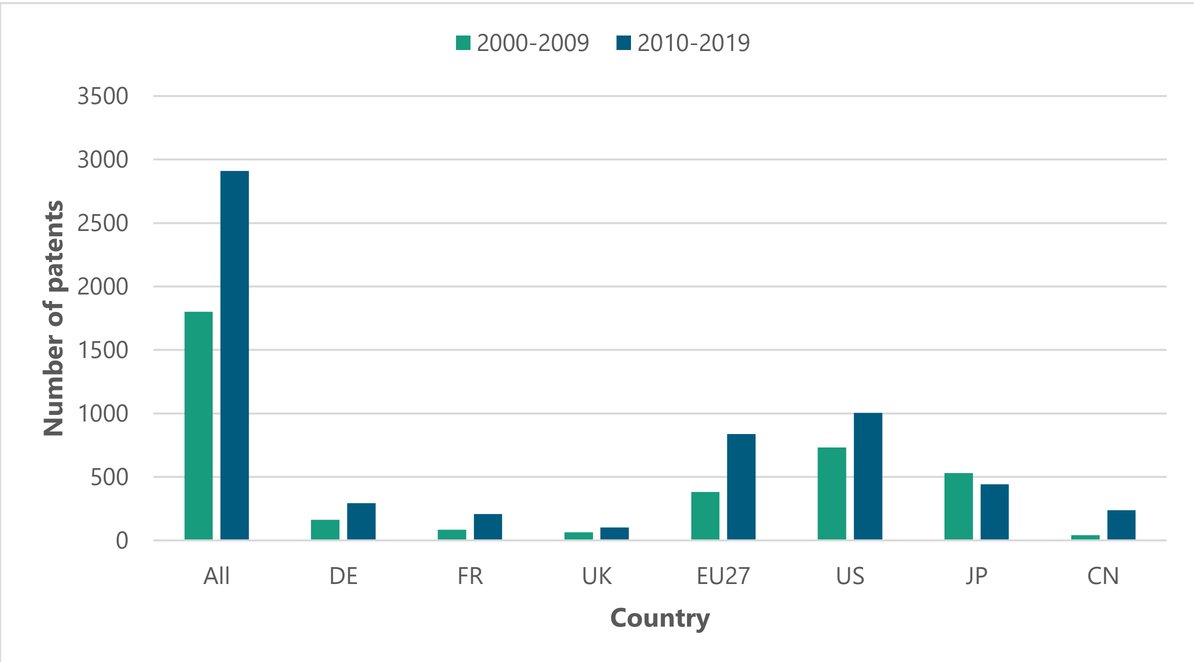
Figure 4: Publications for bio-based plastics 2000-2021



Source: Fraunhofer ISI based on Scopus

Regarding patents, the worldwide number are significantly higher 2010-2019 compared to 2000-2009. This applies for every included country, except for Japan. The US are slightly ahead of the EU-27. Germany covers 39% of the EU-27 patents on average in the last 20 years. China, France and the EU-27 in general more than doubled the number of patents in the two time periods. When just focusing on the relative growth, China made the highest progress since 2014.

Figure 5: Transnational patents for bio-based plastics, comparison of 2000-2009 and 2010-2019

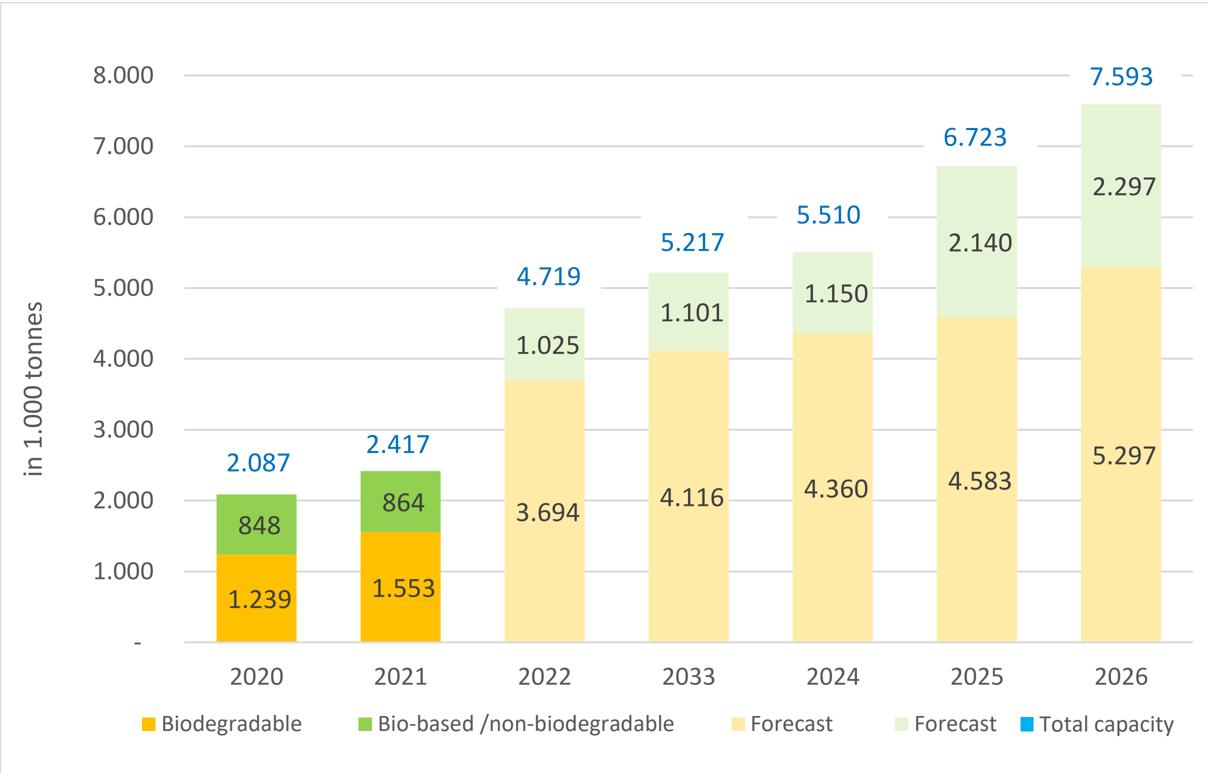


Source: Fraunhofer ISI based on STN

4.3 Market Outlook

Currently, bio-based plastics still represent a niche with a share of *one* per cent (appr. 2 to 4.6 million tons) of the 320 million tonnes of plastic produced annually[13]. But the market has grown steadily in the last 15 years (Wydra et al. 2020; European Bioplastics 2017). Forecasts for European bioplastics production capacities[14] project an increase from around 2.42 million tonnes in 2021 to approximately 7.6 million tonnes in 2026. The share of bio-based plastics is projected to grow from currently less then 1 to over 2% of all plastics. Some market forecasts are even more optimistic for the decade and project a market share for bio-based plastics in Europe of up to 5% until 2030 (emergen Research 2022). But equivalent 5-year forecasts for bio-based plastics have been failed continuously in the last decade (Wydra et al. 2020)

Figure 6: Global production capacities of bioplastics



Source: https://www.european-bioplastics.org/market/

The strongest market growth is forecasted for biodegradable products, namely PHA and PBAT[15].[16] Regarding applications, fibres including woven, non-woven (mainly cellulose acetate (CA) and polytrimethylene terephthalate (PTT)) have the highest share with 24 %. Packaging, flexible and rigid, also have a 24 % share in total, followed by automotive and transport with 16 % (mainly epoxy resins, PUR and aliphatic polycarbonates (APCs)), building and construction with 14 % (mainly epoxy resins and PA), consumer goods with 9 % (mainly starch-containing polymer compounds, PP and casein polymers).

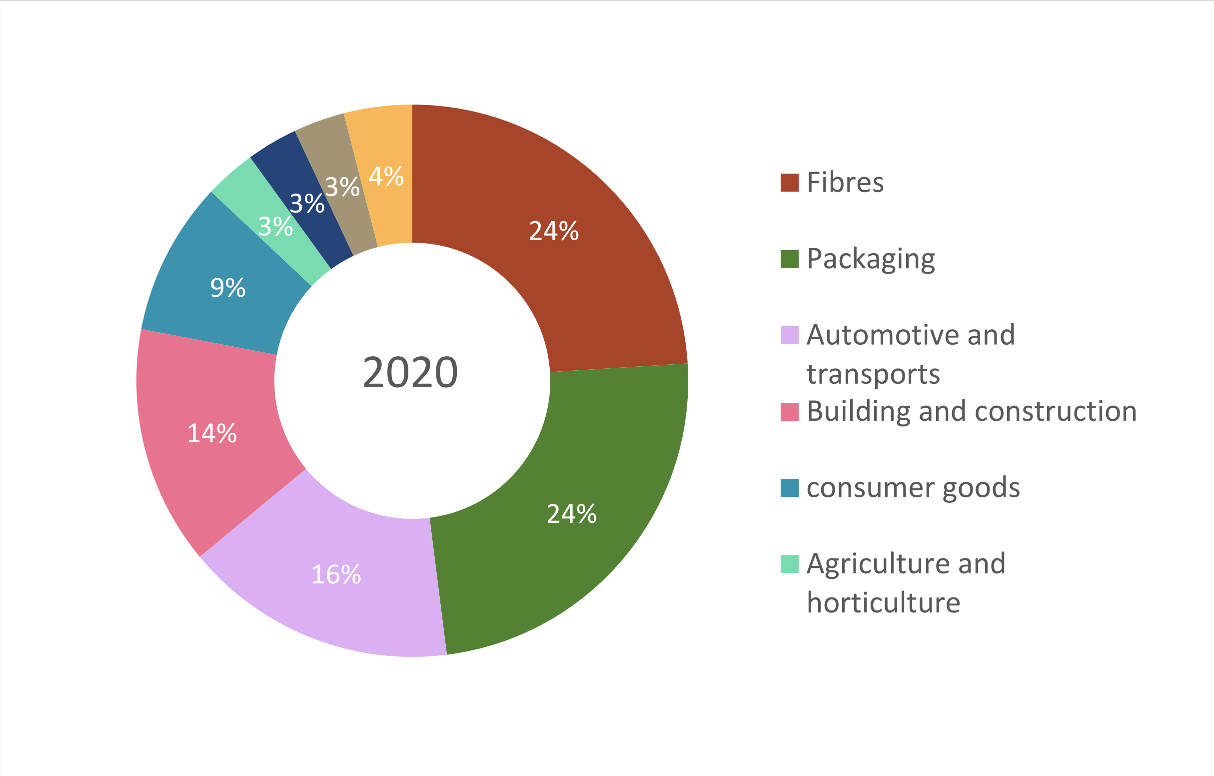
[13] https://www.european-bioplastics.org/market/

[14] Production capacities may differ from actual production volume, but usually there is no information about actual volume available

[15] Polybutylenadipat-terephthalat

[16] http://nova-institute.eu/press/?id=237

Figure 7: Shares of the world-wide produced bio-based polmers in different market segments in 2020



Source: http://nova-institute.eu/press/?id=237

4.4 Potential Impact

Economic Impact

The information on the contribution of bio-based plastics to the German economy is limited. The EU possesses considerable production capacities for bio-based plastics with a share of 24 percent of world-wide capacity. However, this share will probably decrease, as - based on the current announcements of investments - Asia is predicted to have passed the 70 percent share by 2026[17]. While it is clear that no large plant in Germany currently exists, it is not known to which extent large firms actually produce bio-based plastics in Germany, as it is not disclosed by the firms and is not separately documented in official statistics (Wackerbauer et al. 2019). There are some German firms that are active in bio-based plastics, but not many. As outlined above, the production is predicted to take mainly place in Asia, so the effects are mostly limited to effects on the user side (resources substitution, etc.).

Interestingly, there have been several attempts to model the diffusion and future impact of bio-based plastics in Germany (Döhler et al. 2022; Horvat et al. 2018; Jander 2021). Depending on the policy assumptions, some potential impacts on market, diffusion and resource substitution are identified, but economic impact being assessed.

Environmental Impact

[17] https://www.european-bioplastics.org/market/

While quite a considerable set of analysis provide optimistic results regarding potential CO_2-savings by bio-based plastics - e.g. bio-based plastics could potentially save 241 to 316 Mio. t of CO_2-equivalents per year globally (Spierling et al. 2018) - the farming and processing of plants used for bio-based plastics pollute soil and water heavily.[18] Hence, the sustainability of bio-based plastics is highly disputed. Moreover, there are intensive methodological debates about how to measure the sustainability of bio-based plastics[19].

One point of discussion has been potential land-use of effects of bio-based plastics. The European Bioplastic Association emphasizes that the demand of renewable feedstock for bioplastics is low and competition to food and feed limited.[20] They estimate the world-wide land demand to 0.7 million hectares (0.01 percent of the global agricultural area) and projected to rise to 2.9 million hectar, this represents 0.06 percent of the global agricultural area. Hence the Association claims that effects are limited. However given the expected growth rates of bio-based plastics and the shortage in land in future for food-crops in the coming decades implies that each hectare of non-food crops produced on arable land contributes to the global expansion of cropland and loss of biodiversity and add emissions.

An important discussion concerning environmental impact is to which degree bio-plastics are produced and consumed in circular value chains. This depends on how practically the will be compatible with existing recycling streams and infrastructures, to which extent they can be produced or re-used by material recycling and how consumption patterns and waste streams evolve.

4.5 Summary of relevance and suitability for case study selection

Bio-based plastics are an ambiguous case in the bioeconomy. On the one hand, they have received rather high attention in the public compared to many other bio-based segments as the potential and relevance for daily life can be shown. Moreover, the different innovations paths and issues (e.g. drop-ins vs non-drop-ins; issue of biodegradability, policy topics) are reflected in the case of bio-based plastics, and they have a pioneering function for rather large scale-production in the bioeconomy. On the other hand, expectations of future relevance of bio-based plastics have not been fulfilled in the past: Bio-based plastics have been stagnating at a limited share of overall plastics production. The acceptance and image of bio-based plastics is ambiguous, as sustainability performance and the contributions to some of the related challenges (e.g. environmental pollution by microplastics) are limited or at least disputed.

Regarding a possible case study, the bio-based plastics case would serve very well to analyse more closely various kind of issues: The data availability of bio-based plastics is comparably good in terms of market assessments. For economic data questions remain, e.g. how to potentially integrate market data with official sectoral statistics on NACE level for potential estimations that may serve as an input for modelling. Moreover, bio-based plastics could also serve as an analysis example of potential transition to circular economy and also to look what kind of impact may arise from such developments e.g. what it means for the bio-based share analysis to have more circular flows, on the needs of land resources, etc.

[18] https://www.umweltbundesamt.de/biobasierte-biologisch-abbaubare-kunststoffe#11-was-ist-der-unterschied-zwischen-biobasierten-und-biologisch-abbaubaren-kunststoffen

[19] See e.g. https://www.european-bioplastics.org/jrcs-plastics-lca-method-is-not-fit-for-purpose/

5 Technology Field of Algae

5.1 Characterization of the technology field

5.1.1 Definition and Delineation

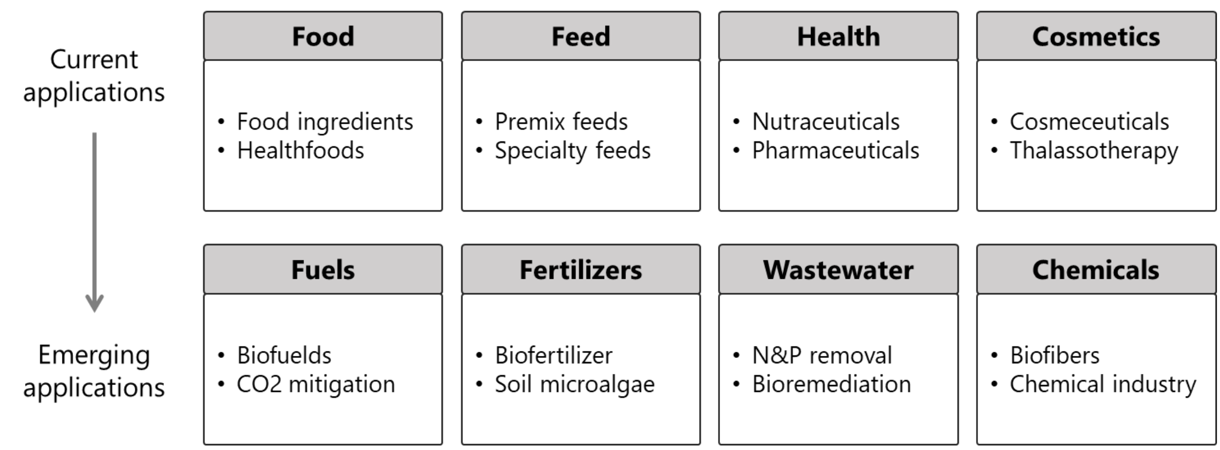
Algae are a diverse group of aquatic organisms capable of photosynthesis, using sunlight as energy source and CO_2 as carbon source, and producing biomass and oxygen by this process. There are more than 70 thousand species of Algae in the world. About 80% of Algae species are unicellular and are called microalgae, the other 20% are multicellular and are called macroalgae (Araújo 2019). Macroalgae are important habitat-structuring species in coastal ecosystems, while microalgae constitute the basis of the marine and aquatic food chain (Araújo et al. 2021a).

5.1.2 Current status and potential future developments

Algal biomass has been used for centuries by coastal communities as fertilizer, livestock feed and food. Currently, it is mainly used by the food and chemical industries. New applications based on algal biomass have been developed in recent decades and comprise feed and nutritional supplements, pharmaceuticals, third generation biofuels, biomaterials and bioremediation services. These new applications have led to an increase and diversification of the market for algal biomass (Barbier und Charrier 2019) (Figure 8). Algae-based compounds of commercial interest include pigments, lipids, polyunsaturated fatty acids, proteins, polysaccharides and phenols. The market for Algae products is expected to be led by the nutritional supplements sectors in the coming years.

Macroalgal biomass for commercial use is either harvested from wild stocks or produced in aquaculture. Annual commercial use of macroalgal biomass has increased globally since 1950, reaching 32.67 million tons in 2016. Global commercial use of macroalgaeis mainly based on aquaculture. The share of the EU in global macroalgal biomass is less than one percent which most of it comes from harvesting wild stocks (98% in 2016) (Araújo 2019). Microalgae are traditionally grown in simple open ponds, but research and technological advances in recent decades have led to a variety of highly productive bioreactor concepts. The price of microalgae biomass ranges from 5 to 500 €/kg, with a production volume of up to 100 kt/year (Fernández et al. 2021).

Figure 8: Current and emerging applications of Algae



Source: (Fernández et al. 2021))

There are several drivers and barriers for the further utilizazion of algal products listed in Table 3

Table 3: Drivers and barriers for Algae

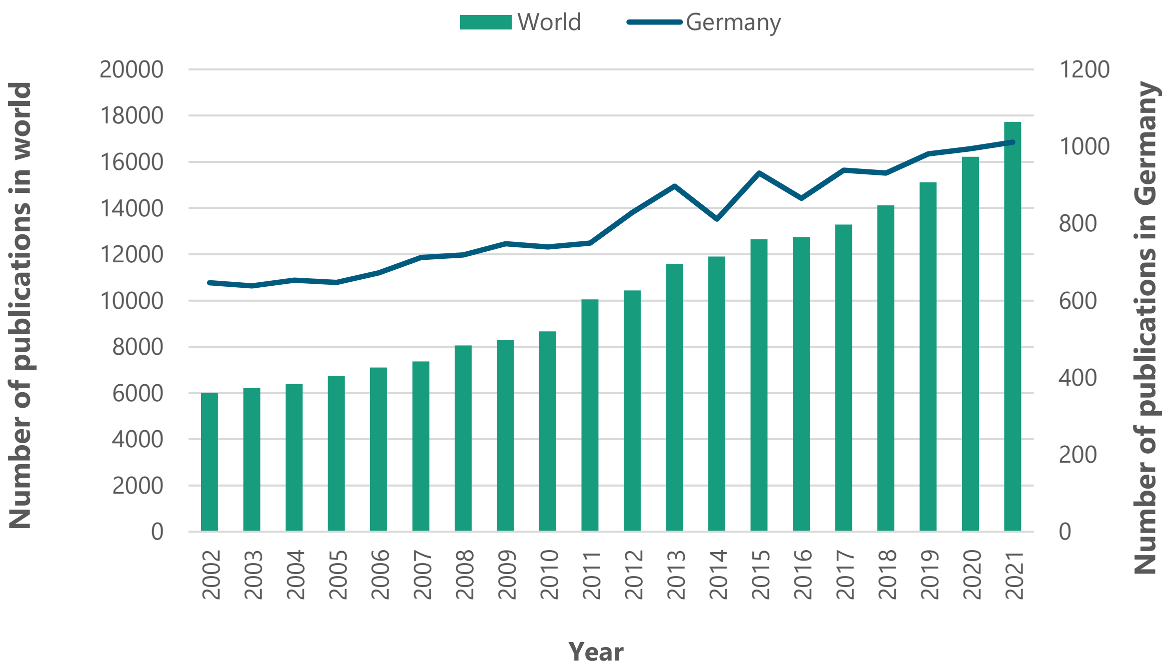
Drivers	Barriers
Algae Consumption in Europe	
High demand for diverse dietary supplements due to increasing health awareness.	Consumer hesitance due to unfamiliarity with Algae-based products.
A growing preference for eco-friendly products as part of sustainability efforts.	Regulatory hurdles for introducing new Algae products.
Supportive EU policy framework for sustainable food alternatives.	Perception of higher cost of Algae products versus traditional alternatives.
Algae Production in Germany	
Progressive environmental policies in the EU, including the forthcoming Algae strategy, provide a conducive environment for Algae production.	High cost competitiveness in low-cost applications could dissuade investment into Algae production.
A burgeoning interest in sustainable biofuel production has sparked research into the possibilities of Algae-based biofuels.	The geographical and climatic conditions in Germany may pose challenges to production factors such as light availability, temperature, and pH balance.
The potential for using Algae for carbon sequestration and water purification could incentivize the local production of Algae.	The introduction of non-native species and potential environmental stressors like global warming and water quality decline could hinder Algae production.

Source: Barbier und Charrier (2019), Araújo (2019), Fabris et al. (2020)

5.2 Publications and Patents

The publication analysis for the Algae field indicates a slight rise of publications over time since two decades ago (Figure 9). The growth in number of relevant publications in Germany is fairly aligned with the world-wide trends. Germany's share of world wide publications has been declining from around 10% in the early 2000s to around 5% in the early 2020s. The total number of scientific publications on Algae is only slightly growing in the recent years.The publication analysis for the Algae field indicates a slight rise of publications over time since two decades ago (

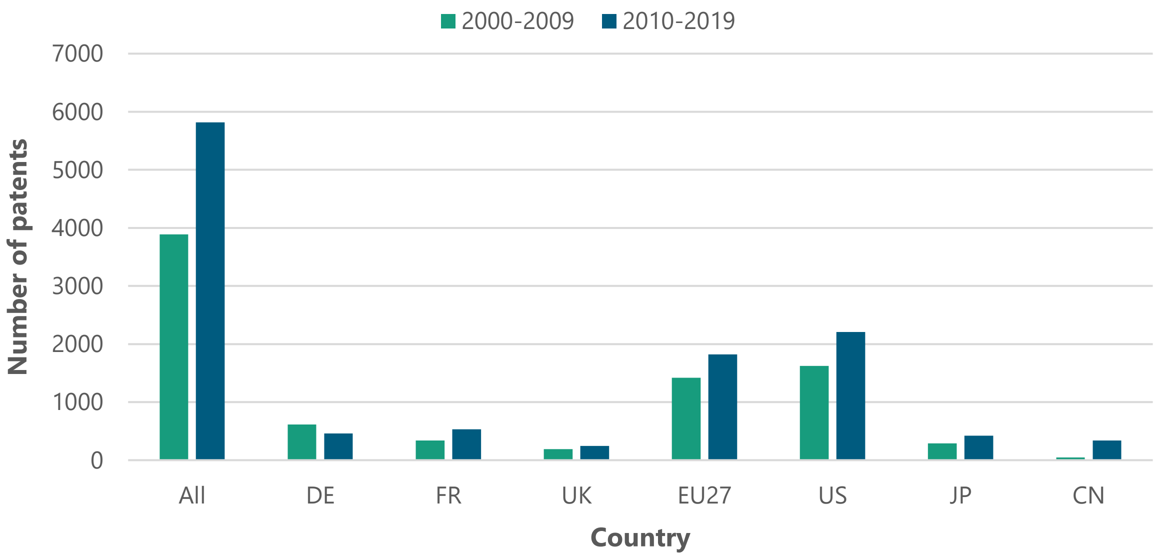
Figure 9: Publications for Algae 2002-2021



Source: Fraunhofer ISI based on Scopus

Concerning to patents, the overall trend had been growing, particularly in the US and EU, from 2000 to 2009 (graphs not presented). There is a sharp drop in year 2010 probably because of falling oil price. The number of patents on Algae started to grow again in the last years. In contrast to the US and the EU, China has been increasingly generating patents in Algae since 2013. The EU-27 is in total a bit lower than the US in patenting, with Germany generating in average about one-third of the EU's patents in the recent two decades (Figure 10). France and Germany are leading in terms of patents in the EU. After US and EU, Japan and China have the higher number of patents around the world.

Figure 10: Transnational patents for innovative Algae applications, comparison of 2000-2009 and 2010-2019



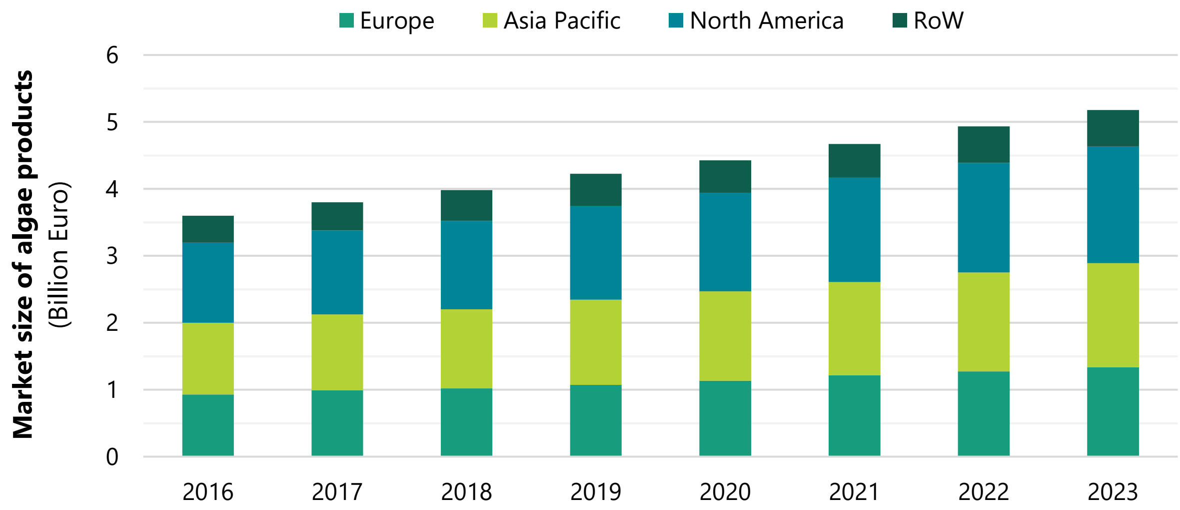
Source: Fraunhofer ISI based on STN

5.3 Market Outlook

In 2016, the value of the global Algae products market amounted to Euro 3.6 billion and it was estimated to reach over Euro 5.2 billion by 2023 (Statista 2020) and Euro 6.3 billion with CAGR of 5.9% between 2021 and 2028[21]. As of 2021, the estimated market value of Algae products in Europe amounted to just over 1.2 billion Euro. In the same year, the Algae market was valued at some 1.6 billion Euro in North America (Figure 11).

[21] https://www.credenceresearch.com/report/algae-products-market

Figure 11: Global market size of Algae production by region 2016 - 2023 (Statista 2020)



Source: (Statista 2020)

In the global Algae products market, the major countries are US, Canada, China, Japan, Australia, New Zealand, Brazil, Germany, France, and Spain. The United States dominate the North American market using Algae ingredients mainly in cereal, energy bars, ice cream, and chocolate making (Araújo 2019). These key players are concentrating on new product developments as well as technological innovation to enhance their production of Algae products. The key players in the global Algae Products Market in terms of value and volume include DuPont (US), Cargill (US), DSM (Netherlands), BASF (Germany), Corbion (Netherlands), E.I.D Parry (India), CP Kelco (US), Fenchem Biotek (China), Algatech (Israel), and Cyanotech Corporation (US). In addition, some regional and country-specific players are investing heavily to expand their product portfolio and increase sales (Araújo 2019). In Germany, there are several experimental, pilot and demonstration microalgae production plants in which CO_2-containing waste gases from industrial production processes are used as a carbon source for photoautotrophic microorganisms. There is no macroalgae production facility in Germany.

There were 126 Algae-producing companies in the EU running a total of 144 production plants, and 15 producing companies outside the EU (Faroe Islands, Greenland, Iceland, and Norway) running one plant each in 2019 (Araújo 2019). The majority of companies are located in France, followed by Spain, Ireland and Germany. Microalgae production is dominant in Germany. Overall, photobioreactors are the most commonly used systems for microalgae production. Available data and information on microalgae are very fragmented in the EU.

5.4 Potential Impact

Economic impact

Algae contribute to the global primary production while also playing an important role in the uptake of dissolved nutrients from the surrounding environment, coastal defense from hazardous waves and potentially in carbon sequestration, thus providing important ecosystem services.

However, the Algae sector is still immature and relatively small in the EU. Its future growth depends on technical innovations to increase production and, at the same time, reduce production costs. Commercial applications of Algae such as biofuels, bioremediation or biomaterials or pharmaceuticals have only a small share in the EU (Araújo et al. 2021b). One of the challenges for these products is the separation of target substances from the water matrix of the cells, which requires significant energy inputs, rendering these processes rather inefficient. Further technological advancements are needed to overcome this limitation and enhance the overall efficiency of algae-based product manufacturing. In the case of macroalgae products, the EU and Germany are potentially importer. Current data by the JRC displays that there are 18 Algae-related production or manufacturing companies in Germany (none for macroalgae) with around 150 employees.[22]

It is difficult to assess what magnitude of economic effects may be achieved in the case EU policy initiatives are successful. It is uncertain whether a significant production of biomass from Algae is realistic, which could imply the build-up of EU internal bio-based value chains including higher domestic availability of biomass and lower imports. The EU production in macro-and microalgae Algae was 0.027 Mt (based on 10-year averages of recent data), contributing to less than one percent of the global Algae production (Camia et al. 2018). In the case of an expansion of microalgae, an industrial niche with high-tech products may emerge, but unclear magnitude.

Ecological impact

Despite the potential advantages offered by algae farming in various sectors, it is essential to consider and address the possible negative consequences associated with its production. Unsustainable macroalgae farming practices in deltas, river mouths, and coastal areas can exacerbate nutrient pollution, leading to detrimental effects such as eutrophication and damage to local ecosystems. Moreover, overcultivation of macroalgae in aquatic environments may endanger the habitats of aquatic species over time, and excessive harvesting of wild stocks can further disrupt coastal community structures (Araújo 2019).

Moreover, algae cultivation, which has the potential to mitigate nutrient losses and greenhouse gas emissions and provide "green" energy (Ullmann und Grimm 2021), could also lead to significant negative impacts on the local environment if not managed carefully. Therefore, it is crucial to thoroughly evaluate and address these potential environmental consequences in order to ensure sustainable algae production practices. It is important to recognize that some aquaculture systems, particularly those used for fish farming, can be energy-intensive and contribute to environmental problems. The feedstock used for these systems may also raise sustainability concerns. Furthermore, algae growth requires light, raising questions about the use of artificial light sources and their associated energy demands, as well as the land area required for open ponds. In general, plant growth in water tends to be less productive per hectare than plant growth on land.

To support the sustainable development of the algae sector in Europe, it is crucial to gather more evidence on the natural dynamics of wild resources, the impact of various harvesting methods, and the growth potential of aquaculture production. Establishing sustainable and responsible management practices as well as limit of exploitation will be essential to mitigating the adverse impacts of algae production on the environment and ensuring that its potential benefits can be fully realized.

Social impact

The social impacts of algae production encompass various aspects, such as local communities, employment opportunities, and public health. While the industry can stimulate local economies and create jobs, it is essential to manage the expansion responsibly to avoid conflicts with existing land and water uses or cultural practices. Algae products offer nutritional benefits, but potential risks, such as contamination with harmful substances, must be addressed through strict regulations. In

[22] https://knowledge4policy.ec.europa.eu/visualisation/bioeconomy-different-countries_en#algae_prod_plants

summary, careful management and responsible growth are crucial to balance the positive and negative social impacts of algae production in the EU.

5.5 Summary of relevance and suitability for case study selection

Algae may have some potential to produce biomass more rapidly and cost-effectively than traditional crops, in some cases. High-tech microalgae-based solutions could be employed across various industrial value chains, however the uncertain environmental impacts and relatively high costs of production still slow down its development. However, despite political interest and the potential for algae production to become an innovative sector within the EU bioeconomy, it remains uncertain whether Europe, particularly Germany, will establish a significant industry in the foreseeable future, especially concerning macroalgae.

Microalgae are currently utilized for a limited number of industrial applications in Germany, but potential exists for expanding microalgae agriculture for food and feed additives, bioproduct sourcing, bioremediation, and carbon sequestration. The microalgae industry does provide biomass for food and nutrition, but its scope is limited to a few algae species and applications. Overcoming significant technological challenges is essential for the increased use of algal products. Germany has the opportunity to contribute to the technological advancement of large-scale microalgae photobioreactors, highlighting the need for R&D to develop technological processes and suitable business models for algal biomass utilization. Presently, data on microalgae in the EU and Germany is rather fragmented.

Regarding the suitability for a case study, the uncertain relevance of macroalgae for Germany and the limited relevance of microalgae activities for outcomes such as biomass availability and ecological effects suggest that this technology field may not be of substantial interest from a monitoring perspective. Additionally, extensive bottom-up data analysis has already been conducted by the JRC at the country level, which may limit the added value of a case study.

6 Technology Field Indoor Vertical Farming

6.1 Characterization of the technology field

6.1.1 Definition and Delineation

Indoor vertical farming is a multi-layer system of growing plants by using a mixture of water and the required minerals in a soilless controlled environment with a total replacement of solar radiation with artificial lighting (Avgoustaki und Xydis 2020; Mempel et al. 2021).

In indoor vertical farms, plants grow in soilless cultivation systems such as hydroponic, aeroponic or even aquaponic systems (Avgoustaki und Xydis 2020), in a completely isolated space from outdoor environment with thermally insulated installations and airtight structures that give the opportunity to the farmers to control the environment in terms of temperature, humidity and CO2.

6.1.2 Current status and potential future developments

Indoor farming operation is featured by widespread technology deployment. Artificial lighting is widely used to supplement the daily integral needs of plants. Environmental control systems and sensors/controllers are also widely used in indoor farming systems, where Internet of things (IoT), big data, and analytics play a key role. The control systems are integrated with the information or computing platforms that enable continuous remote monitoring of the structure and production system. Automated seeding, transplanting, and harvesting processes associated with robotic technologies are less utilized in the current ecosystem, but it is anticipated that due to the labour intensity required in indoor farming environments, increased use of such technologies will lead to greater efficiencies in the industry (Petalios 2018).

Recently, the introduction of robot harvesters, automatic seed planters, and greenhouse roof cleaners have positively impacted the vertical farming market by reducing various costs indulged with it. However, it is crucial to consider the potential impact of such automations on job opportunities within the bioeconomy. Development of indoor vertical farming may not have a significant impact on the labour shift in the sector in the coming years, as the integration of advanced technologies may create new roles and skill requirements. Additionally, a thoughtful and strategic approach to technology implementation can foster a hybrid system that combines human expertise with automation, thereby promoting efficiency and productivity while maintaining a demand for a skilled workforce. As the bioeconomy transitions and indoor vertical farming expands, it will be essential to address these labor-related aspects to ensure a sustainable and inclusive future for the agricultural industry. Hence, there are major driving and restraining factors affecting the development of the overall vertical farming sectors(Table 4). In the time span of 2022 to 2030, the indoor vertical farming market is expected to observe considerable growth in building-based segment, aeroponics method, and production of biopharmaceutical products (Grand View Research 2022).

Table 4: Drivers and barriers for development of indoor vertical farming

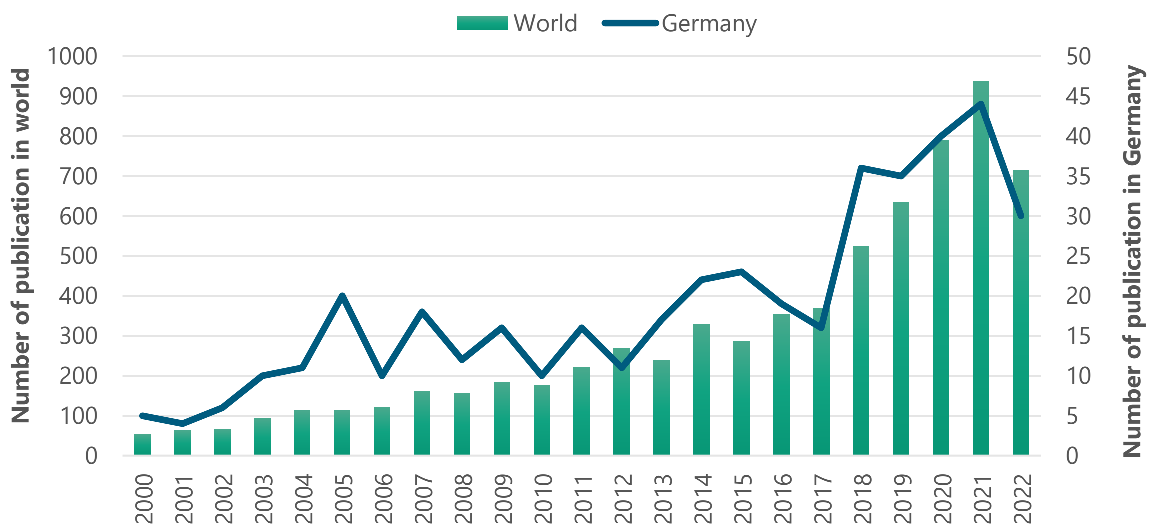
Drivers	Barriers
Increased harvest cycles and higher yields (Petalios 2018)	High costs for initial investment (Market Future Research 2022)
Independency from weather conditions and seasonality (Petalios 2018)	High operational costs (Agritecture 2018)

Limited use of pesticides, fertilizers and ripening agents (Petalios 2018)	High market risks due to technological uncertainty, long returns, market size and purchasing preferences of retailers (AgFunder 2019)
Extremely high efficiency in land use (Petalios 2018)	Limited variety of crops (e.g. lettuce, herbs, tomatoes and berries (Avgoustaki und Xydis 2020).
Growing consumer demand for organic and environment-friendly food products (Market Future Research 2022)	Adverse impacts of Covid 19 pandemic (e.g. reduced demand for high-quality products, shortages in personnel (Market Future Research 2022).

6.2 Publications and Patents

The publication analysis for the whole field of indoor vertical farming indicates an on-going rise of publications over time with a sharp increase since 2018 world-wide (Figure 12). The growth in number of relevant publication in Germany is relatively aligned with the world-wide development. The Germany's share of world wide publications has been fallen from around 10-12% in the early 2000s to around 4-5 % in the early 2020s.

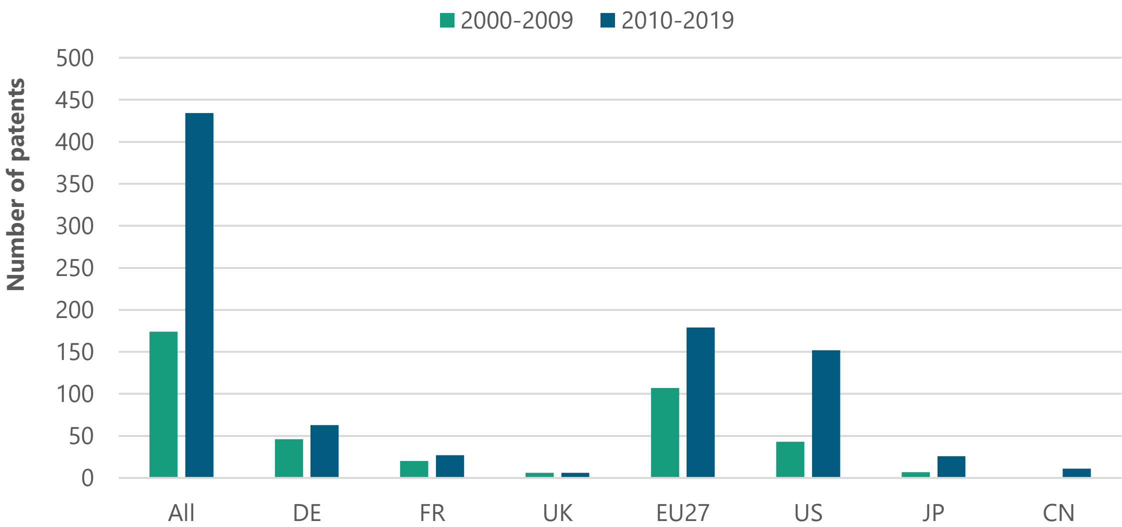
Figure 12: Publications for bio-based surfactants 2000-2022



Source: Fraunhofer ISI based on Scopus

Regarding to patents, the overall evolution is rather stable with a slightly lower number of patents in 2000-2009 compared to 2010-2019 (Figure 13). The EU-27 is in total slightly ahead of the US in patenting, with Germany generating about 40% of the EU's patents. Japan and China are getting to register more patents in the recent years, but they are quite behind the US, Germany and of course the EU. Additional patent analysis (graphs not shown) show a substantial rise in the number of patents in indoor vertical farming since 2018. Germany is leading in terms of patents in the EU.

Figure 13: Transnational patents for indoor vertical farming, comparison of 2000-2009 and 2010-2019



Source: Fraunhofer ISI based on STN

6.3 Market Outlook

Indoor vertical farming has attracted the attention and interest of big investors, given the fact that it involves the use of highly sophisticated technologies and the intense vertical use of space, achieving high yields compared to traditional methods (Avgoustaki und Xydis 2020). Considering the adoption of emerging technologies (i.e. Agriculture 4.0) and consumer demands, indoor vertical farming may play an important role for provision of fresh products to inhabitants of infertile regions (e.g. Arctic, Antarctic, deserts) which otherwise cannot be imported for logistic and perishability reasons. Another option is mega cities where agricultural areas are far from the densely populated city, and indoor vertical farms may contribute to providing fresh food to those inhabitants.

The global market size value of indoor vertical farming is EUR 5.5 billion in 2020, and it is estimated to grow at a compound annual growth rate (CAGR) of 24.3% to reach about EUR 20 Billion by 2026 driven by the increasing awareness on health and food sustainability (Statista 2022b). In the regional view, North America held a majority market share of EUR 1.375 billion in 2020 (Statista 2022b). The North American regional market is expected to witness significant growth continuing the expansion of small-scale, commercial vertical farms (Grand View Research 2022). Europe, Asia-Pacific and rest of the world held respectively 1.353, 1.254, and 0.665 billion Euros share of market in 2020. In the national view, Germany is the forth country, with a CAGR of 16.9%, after US, China and Canada between 2020 and 2026 (Statista 2022b).

The companies in the sector act as food producers, technology providers and consultants. Some companies from the vertical farming sector are listed in Table 5.

Table 5: List of flagship installations of indoor vertical farming

Company	Country
Nordic Harvest	Denmark
Jones Food Company	UK
Kalera AS	Germany
Future crops	Netherlands
Gronska Stadsodling	Sweden
Growing Underground	UK
Infarm	Germany
Harvest London	UK
Growy	Netherlands
Create to Plate	UK

6.4 Potential Impact

Recent technological developments in indoor vertical farming, to some level, may cause disruption in the agrifood system by boosting the production of high-quality food with less environmental impact in the food markets. Indoor vertical farming has its own advantages and disadvantages compared to conventional farming as follow:

Economic contribution

The product quality is considerably increased in the indoor vertical farming systems due to precision measurement and a suitable plant growth factor adjustment. The improved weights, size and quality of product and less defects bring more value added to the products (Santiteerakul et al. 2020). Depending on the farm's scale, products and energy and investment costs, the productivity may be higher in indoor vertical farming compared to conventional farming because of the reduced input costs (e.g. water, land, fertilization and labour) and the increased product weight per unit (Mir et al. 2022). The high investment costs are the main restricting factor for cost efficiency of indoor vertical farm's products. Thanks to recent advancement in digital technologies, the productivity is expected to grow further in indoor vertical farming.

Ecological contribution

The indoor vertical farming has the potential to be resource-use efficient and environmentally friendly compared to conventional farming in certain aspects, such as water consumption, land use, usages of fertilizer and pesticides, and waste management (Avgoustaki und Xydis 2020). However, it is important to acknowledge the high energy consumption associated with indoor vertical farming systems, mainly due to artificial lighting and environmental control systems. The energy intensiveness of indoor vertical farming can offset some or all of the ecological benefits, depending on the energy source utilized. As the sector matures, there is a need for further research and innovation to improve energy efficiency and utilize renewable energy sources to minimize the environmental impact (Al-Kodmany 2018). In addition to energy considerations, the construction of indoor vertical farming facilities raises concerns about the materials used, particularly if the buildings are made of concrete (beton). Concrete is associated not only with operational energy costs but also with embodied carbon emissions, which can significantly contribute to the overall environmental footprint of the facilities.

Social contribution

Indoor vertical farming contributes in regional food security, food safety and traceability of products for consumers. The indoor vertical farming system may increase demands for fresh food, nutritious food, and functional food for health care and higher quality of life because of high controllability of plant environment. In addition, vertical farming offers an opportunity to support the local economy by converting abandoned urban buildings into vertical farms to provide healthy food in neighbourhoods where fresh produce is scarce (Al-Kodmany 2018). There is a possibility of disadvantages related to low-income housing in the context of indoor vertical farming. While indoor vertical farming offers several benefits, there are potential challenges and concerns that need to be considered, particularly when it comes to social equity and inclusivity.

6.5 Summary of relevance and suitability for case study selection

Indoor vertical farming is an emerging farming practice for growing high-value fresh food and medicinal plants in totally controlled indoor environments in or near by urban areas. Vertical indoor farming bears the potential to deliver high quality fresh vegetables and herbs close to the site of consumption, thereby reducing transport distances. Moreover, costs and environmental benefits are expected from higher yields and less agricultural inputs (e.g. fertilizers, water, pesticides) than in conventional agri- or horticulture. Disadvantages are very high investment and operational costs, especially for artificial lightning.

For these reasons, the current contribution to vegetable production is negligible and will remain so in the coming years, despite high predicted market growth rates. Vertical indoor farming at present only seems to be an opportunity for providing food in non-arable regions (e.g. arctic, deserts, high mountains, contaminated sites), in mega-cities, or in abandoned built environments (houses, mines) where existing infrastructures can be reused. The success of the indoor vertical farm depends on the general technological advancements, regional innovation environment and local conditions including energy source and price, demand on certain products by population, availability of labors, and farming conditions.

However, vertical indoor farming is a high-tech option and can be understood as a specific sector within agriculture 4.0 and smart farming. As such, it is an innovative and attractive field for suppliers of digitalized agri- and horticultural equipment, of regenerative energy solutions, of sensors, of automation etc. Here are potentials for the German industry, and perhaps an opportunity for diversification of suppliers presently active in the automobile sector.

There is not much available data on the extent and revenue of indoor vertical farmers in Europe and Germany. E.g., there are no estimations available to which extent vertical indoor farming may contribute to biomass provision. Due to uncertainty about economic and environmental impacts of indoor vertical farming as well as potential market size of Germany in the coming years, indoor vertical farming may not be an ideal option for a case study.

7 Technology Field Wood-based Applications

7.1 Characterization of technology field

7.1.1 Definition and Delineation

Innovative wood-based applications in the bioeconomy refers to the sustainable and new use of wood, forest-based products, and their derivatives as a source of energy, bio-fuels, biochemicals, and a broad range of materials in a variety of businesses and sectors. Wood-based value chains cover all phases from the primary production of wood to the manufacturing of end goods, taking into consideration the reuse and recycling of wood-based products (e.g., recycled paper), and the use of transformation leftovers (e.g., sawdust) (Robert et al. 2020).

7.1.2 Current status and potential future developments

Source of input wood-based biomass (e.g., round wood, forest residuals, and wood waste) and kind of products provide insight into the current state and possible future growth of new wood-based applications in the bioeconomy. The segmentation of wood-based applications includes the following:

- Pulp and paper production: This section consists of the manufacture of pulp and paper products such as newspaper, paperboard, and tissue paper.
- Wood products manufacturing: This category encompasses the manufacture of a range of wood products, including lumber, plywood, particleboard, and biochemicals.
- Bioplastics and bioenergy: This section consists of the production of bioplastics, biofuels, and other kinds of bioenergy, including wood pellets and biomass electricity.
- Wood waste recycling: This section covers the collecting, sorting, and recycling of non-/slightly-contaminated wood waste.

Wood-based biomass has a wider range of uses compared to traditional wood products like lumber, paper, and pulp (Hassegawa et al. 2021). Side streams from the pulping process can be utilized to reduce waste and create other products such as lignin for adhesives and resins. Woody biomass that is normally discarded, such as sawdust and branches, can also be used for bioenergy, but availability may become a limiting factor due to increasing demand.(Jarre et al. 2020). The following are examples of innovative wood-based uses within the bioeconomy:

- Cross-laminated timber (CLT) and mass timber products as a sustainable alternative to conventional materials such as concrete and steel for the construction of tall buildings and other infrastructure.
- Bioplastics and biocomposites, which are manufactured from renewable resources and textiles may be utilized to manufacture a wide range of items, including packaging, bottles, and automobile components.
- Biochemicals and bio-based materials: Using the lignin and cellulose of wood to create new bio-based goods such as adhesives, enzymes, solvents, and textiles.
- Utilizing wood charcoal as a natural and effective water purification element in residential water filtration systems.
- Use of recycling streams of wood-based materials for building materials, packaging and others

Innovation is crucial to the growth and development of the global bioeconomy based on wood products. Businesses and research institutions are investing in R&D to support the development of new and innovative products and processes aimed at increasing the sustainable use of wood resources, enhancing the efficiency of manufacturing processes, and reducing the sector's environmental effect. Bio-based chemicals are also an expanding field of innovation, since they contribute to the diversification of the value chain and the production of goods with more added value.

Hence, there are major driving and restraining factors affecting further advancement of innovative wood-based applications (Table 6).

Table 6: Drivers and barriers for innovative wood-based applications

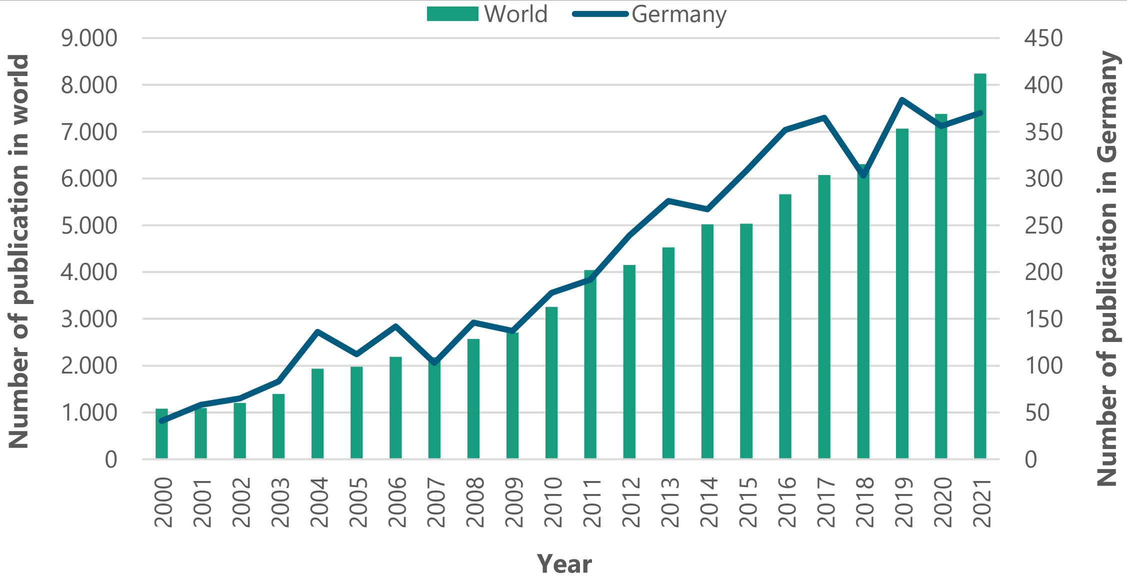
Drivers	**Barriers**
Increasing demand for renewable and sustainable materials: As the world population grows and economies develop, the demand for wood products such as construction materials, paper, and biofuels increases.	Limited availability of resources: The availability of wood resources can be limited in certain regions due to factors such as overharvesting, land-use changes, and poor forest management practices, and poor quality of wood waste.
Climate change concerns: innovative wood-based applications are seen as a way to mitigate the effects of climate change by storing carbon and reducing the carbon footprint of traditional fossil-based materials and industries.	High costs: The costs of harvesting, transporting, and processing wood resources can be high, making it difficult to compete with cheaper fossil-based materials and products.
Advancements in technology: advancements in technology such as biotechnology and precision forestry have increased the efficiency and effectiveness of the wood-based bioeconomy, making it more economically viable.	Lack of infrastructure: Inappropriate infrastructure and logistic chains such as roads and processing facilities, in certain urban and rural areas can make it difficult to collect, transport and process wood resources.
Economic development: developing a wood-based bioeconomy can create new jobs and economic opportunities in rural areas.	Limited Research & development: Lack of Research & development in the field will limit the innovation and development of new products, processes and technologies
Government policies and regulations: Government policies and regulations encourage the development of the wood-based bioeconomy by providing funding for research and development, and by setting standards for sustainable forest management.	Environmental and social concerns: The environmental and social impacts of a wood-based bioeconomy, such as deforestation and displacement of indigenous communities, can be major barriers to its development.

Source: (Cabiyo et al. 2021; Miletzky et al. 2022; Jarre et al. 2020; Jonsson et al. 2021; O Brien und Hennenberg 2023)

7.2 Publications and Patents

Publication data for wood-based applications demonstrates a rising trend over time, with rises of greater magnitude in 2011, 2019, and 2021. (Figure 14). With a few notable exceptions, the number of publications in Germany climbed till 2017. After the greatest decline in 2018, the numbers have been nearly constant since then. Germany's percentage of global publications has often been between 5% and 6%, with occasional exceptions between 4% and 7%.

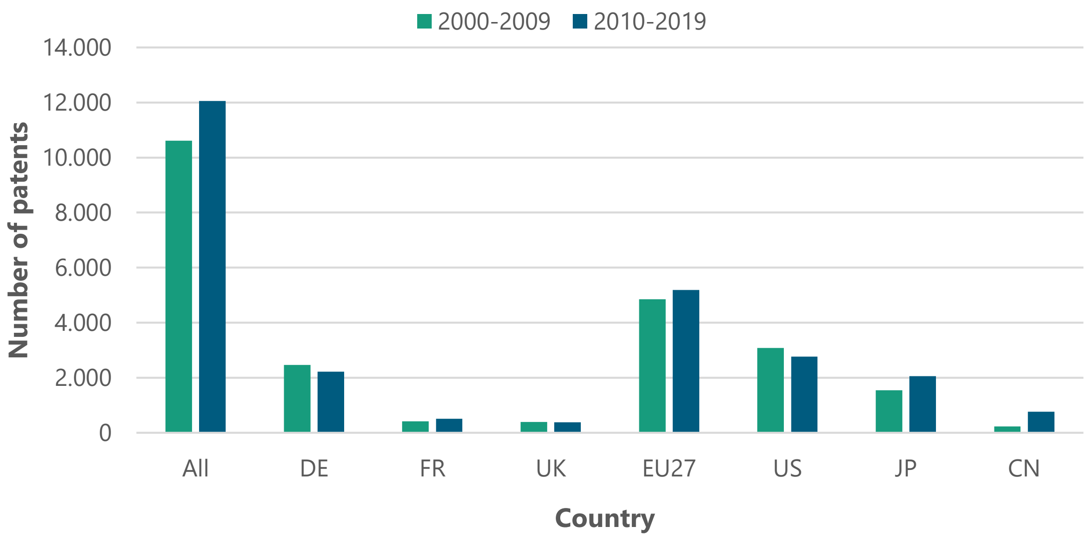
Figure 14: Publications for wood based applications 2000-2021



Source: Fraunhofer ISI based on Scopus

In 2010-2019, there was a modest rise in the number of patents for wood-based applications compared to 2000-2009, according to a review of patent data (Figure 15). The EU-27 is ahead of the United States, although Germany covers an average of 46% of the EU's patents throughout the time period examined. Consequently, it is the top nation in the EU-27 and the second-best nation globally. Yet, only Germany and the United States had fewer patents in the most recent decade compared to the previous decade. China's patents for wood-based applications have increased by more than three times the rate of the United Kingdom. Since 2015, China has thus made substantial gains.

Figure 15: Transnational patents wood based applications, comparison of 2000-2009 and 2010-2019



Source: Fraunhofer ISI based on STN

7.3 Market Outlook

The global wood products[23] market grew from about EUR 650 billion in 2022 to EUR 700 billion in 2023 at a compound annual growth rate (CAGR) of 7.4%[24]. European Wood Product Sales is set to reach EUR 115 billion by 2026 from EUR 109 billion in 2021, growing 0.6% year on year average rate. Since 2016, European market grew 1.9% year on year. In 2021, Germany ranked number 1 in Wood Product Sales at EUR 20 billion. Italy, the United Kingdom and Poland respectively were numbers 2, 3 and 4 in this ranking. Finland rose 18.1% year on year, while Greece fell by 4.3% year on year since 2016[25].

The potential market for wood based products is quite extensive. Market segments such as chemicals are not only responsible for GHG emissions, but also occur at a very large scale. However, it is expected that a very small proportion of traditionally manufactured chemicals will be substituted in the coming 10–20 years (Jarre et al. 2020).

The increasing use of wood as a substitute for non-renewable materials is expected to boost demand for wood products, particularly in construction and textiles. However, production capacities and prices need improvement. The most promising wood products for substitution are mass timber, engineered wood products, and man-made cellulose fiber. The estimated investment requirement for wood processing industries up to EUR 760 billion in 2050[26]. Investments will be required in emerging economies, where industrial round wood supply is increasing.

In Germany, forestry and wood-based product sectors are of high importance, which includes both traditional and innovative applications. These sectors comprise around 115.000 companies and employ more than 1 million people. They contribute 57 mrd Euro.

7.4 Potential Impact

Innovative wood-based applications in the bioeconomy have significant potential for economic growth. According to (Hassegawa et al. 2021) the majority of innovative wood products are direct substitutes (Drop-Ins) for existing products and another third is considered a partial substitute to fossil- based products. Innovative wood-based applications can have many positive impacts, it is important to manage these innovations responsibly to mitigate any negative impacts, such as deforestation and loss of traditional livelihoods. In addition, evaluating the specific innovation and implementing measures to mitigate negative impacts is crucial when planning and implementing innovation in the wood-based bioeconomy.

Economic Impacts

The economic impacts of innovative wood-based applications in the bioeconomy can be complex and multifaceted. Some of the potential economic impacts include (Cabiyo et al. 2021; Robert et al. 2020):

- Research and development of new products and technologies in wood-based bioeconomy can create or save jobs in the fields of research, design, and manufacturing, which may have a positive impact on employment rate. As shown above the forestry and wood sectors are already contribution significantly to the whole economy in Germany.

[23] Wood products refer to a collective term for all the goods and furniture manufactured from wood house including furniture, construction wood, and paper and pulp, and excluding energy wood products.

[24] https://www.thebusinessresearchcompany.com/report/wood-products-global-market-report

[25] https://www.reportlinker.com/clp/global/6326

[26] https://www.fao.org/3/cc2265en/cc2265en.pdf

- Moreover, advancements in technology and production processes can lead to more efficient and productive use of wood resources, which can reduce costs, increase profitability of downstream industries and help the industry to compete with other sectors. In some cases (see above) innovation in wood-based bioeconomy can lead to new products and technologies that can create new business and investment opportunities.

It's worth noting that the economic impact also depends on factors such as how it's managed and planned, along with the regulatory framework. However, the implementation of innovation may come with short term cost and could be seen as a risk by some firms and investors (Purkus et al. 2018). A well-planned, sustainable and responsible wood-based bioeconomy can have positive long-term economic impacts, but one that is not managed responsibly could have negative economic consequences.

Social Impacts

The social impacts of innovation in the wood-based applications in the bioeconomy can include in addition to job creation (Purkus et al. 2018; Robert et al. 2020) :

- Rural development: Developing a wood-based bioeconomy can contribute to rural development by creating new opportunities for economic activity and by supporting small-scale enterprises and an increase in income for people working in the sector or indirectly dependent on it.
- Education and training opportunities: The implementation of new technologies may require specialized skills, which could create opportunities for education and training programs,

However, it's worth noting that not all social impacts will be positive, and innovation in the wood-based bioeconomy can also have negative social impacts, such as displacement of indigenous communities and loss of traditional livelihoods to cases where wood is imported and for applications like manmade cellulosics (MMCFs) (Robert et al. 2020). It is probably much less relevant for Cross Laminated Timber (CLT) produced in Germany from wood sourced within Germany and that is more desirable. Therefore, it's important to take these potential negative impacts into account when planning and implementing innovation in the wood-based bioeconomy.

Environmental Impacts

The environmental impacts of innovation in the wood-based applications in the bioeconomy include:

- Increased resource efficiency: Advancements in technology for production and recycling processes can lead to more efficient and productive use of wood resources, which can reduce the need to harvest more trees or convert more natural areas to forestry use.
- Reduced carbon emissions: Some innovations in the wood-based bioeconomy, such as the development of biofuels, can lead to reduced carbon emissions compared to traditional fossil fuels.
- Increased carbon sequestration: Innovations in the field of precision forestry, biotechnology and sustainable forest management can lead to an increased capacity of forest to store carbon.
- Reduced waste and pollution: New innovations in wood-based bioeconomy such as the development of new wood-based products and technologies may lead to a reduction of waste and pollution in the traditional fossil-based products industries.

However, it is important to note that not all innovations in the bioeconomy based on wood will have positive environmental effects. Regarding environmental impacts, the origin of wood-based biomass is crucially important (Purkus et al. 2018). In the event of overexploitation of forests, certain innovations may result in deforestation, biodiversity loss, and other adverse environmental effects. Wood cascading innovations can help the economy avoid the primary production of round wood. When planning and implementing innovation in the wood-based bioeconomy, it is crucial to evaluate the specific innovation, take into account its potential environmental impacts, and implement measures to mitigate negative impacts (Braghiroli und Passarini 2020).

7.5 Summary of relevance and suitability for case study selection

The wood-based bioeconomy is a growing field that presents a diverse range of products and applications, from molecules to building materials. However, some of these products are still in early development stages or deemed technically and economically unfeasible. The primary goal of the wood-based bioeconomy is to create a more sustainable and efficient use of forest resources, while also reducing dependence on fossil fuels and creating new economic opportunities. By utilizing wood in innovative ways, the industry can help to reduce carbon emissions and increase the efficiency of the entire value chain, if deforestration can be avoided.

The potential product spectrum is very broad and innovativeness as well as information and partly market outlook differs quite significantly between products. Moreover as pointed out above the impact largely depends on the overall volume, cultivation practices and framework giving policies, hence more on macro-level phenomena than on product performances. This makes an in depth-assessment despite its overall relevance, challenging.

8 Technology Field Alternative Proteins

8.1 Characterization of technology field

8.1.1 Definition and Delineation

Whereas no legal definition exists for the European Union, the term „alternative proteins" can be understood to denote proteinaceaous, vegan or vegetarian foodstuffs, which substitute for conventional animal products functionally, either with the aim to fully emulate the latter's organoleptic properties (e.g. meat alternatives) or without it (e.g. some dairy alternatives). The feedstock to produce alternative proteins may stem from different sources, traditionally, from plants such as grains or legumes, but also from insects, fungi or algae. More recently, a cellular-agriculture (cell ag) movement has emerged, which aims to create cellular (i.e. cultivated meat) and acellular (e.g. cultivated milk) animal products using animal cells or microorganisms (Tuomisto 2022)[27].

8.1.2 Current status and potential future developments

Presently, plant-based meat and plant-based dairy alternatives feature the largest markets[28]. In the case of meat, alternative proteins of plant-origin have been available commercially for decades (Aiking und Boer 2006), if not centuries (Shurtleff und Aoyagi 2014). While remaining a niche phenomenon for years, it was only in the recent past that meat alternatives gained momentum. From a technological perspective, their rise was closely linked to developments in extrusion technology, which enabled products closer to conventional meat . R&D efforts aim to bridge the organoleptic gap between alternatives and conventional meat, e.g. taste and texture. In addition to meat alternatives, also milk-alternatives are on the rise, although most plant-based milks still markedly differ from conventional milk.

Compared to the above types of alternative proteins, cellular-agriculture based products constitute a much younger phenomenon. While cultivated meat[29] builds on tissue-engineering technology (Post et al. 2020), cultivated milk and other products rely on fermentation technology (Waschulin und Specht 2018). In line with the nascent state of cellular agriculture, corresponding products are linked to significant risks, uncertainties, and challenges respectively, e.g. when it comes to upscaling production processes. One particular issue regarding meat alternatives e.g. is the search and commercialization for an inexpensive replacement of fetal-bovine serum (e.g.Tuomisto et al. 2022).

So far, Singapore constitutes the only country to officially authorize the sale of Eat Just's chicken, having approved the technology in late 2020 (fleischwirtschaft.de 2020; Vegconomist.com 2020). Similarly, cultivated dairy has been approved for retail sale in the US and in Singapore, yet not in major European countries (Southey 2022). While they profit from various drivers, alternative proteins similarly face an array of different barriers. Table 1 lists some of these for illustration.

[27] In the case of cultivated meat, the cell constitutes the functional unit, whereas in the case of e.g. cultivated eggs, the functional unit is a (mostly) cell-free matrix of different compounds, such as water, fat, and protein.

[28] For example, while a recent study by BCG und blue horizon 2021 found the global consumption of egg substitute to total about 25,000 tons, whereas the authors found the overall production of alternative proteins at the same time to total 857 million tons.

[29] Since therer is no harmonized terminology, the terms „cultivated meat" and „cultured meat" are used synonymously in the text.

Table 7: Drivers and barriers for alternative proteins

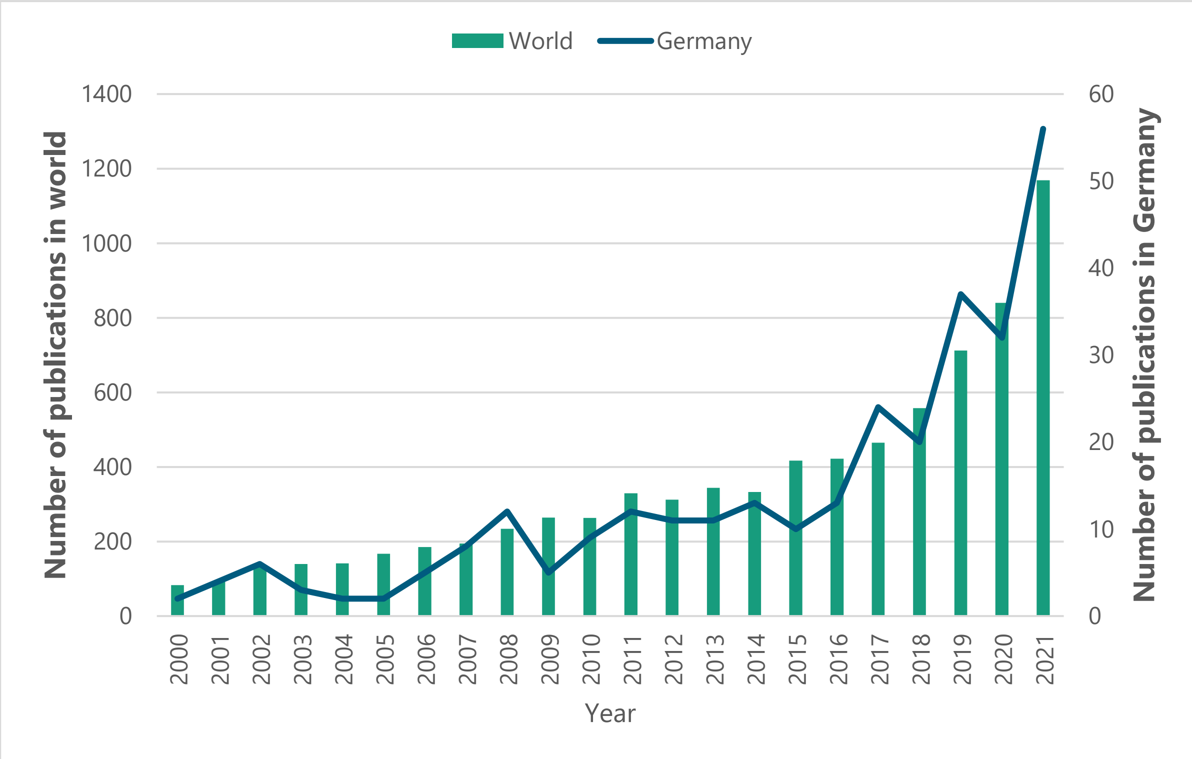
Drivers	Barriers
Trend towards more sustainable diets, e.g. flexitarian, vegetarian or vegan	Food neophobia and a pronounced natural-is-better bias make people cautious of highly-processed foodstuffs such as alternative proteins
Technological progress that allows for improvements in terms of e.g. taste, texture, cost, and nutritional value	Alternative proteins do not yet fully match the organoleptic properties of conventional animal products
Significant private investments in alternative-protein companies internationally	Alternative proteins are highly-processed foodstuffs of varying nutritional quality (e.g. high sodium values in meat, low protein content in milk)
Commitment and investment by large meat incumbents and multinationals	Alternative proteins tend to be more expensive than conventional animal products
	The EU regulatory framework mandates extensive approval process in the case of novel-foods (Regulation (EU) 2015/2283) With respect to cellular agriculture: If GMOs are incorporated into products, the EU provisions of the EU GMO directive apply instead of the novel-foods regulation (Post et al. 2020) With respect to insects: The EU regulatory framework hinders the feeding of insects with low-value types of waste, which would allow using them in a circular way (Regulation (EC) No 1069/2009; Regulation (EC) No 767/2009; Regulation (EU) No 142/2011)
	Limitations with respect to production upscaling, e.g. regarding (public) investments, know-how, or business access Limitations are largest for cell ag products
	Limitations in terms of national/EU labelling regulations, e.g. the use of dairy/meat-related labels for plant-based alternative proteins
	Low maturity of alternative protein niche, e.g. concerning standards/benchmarks, coordination along the value chain, business-planning, wider service ecosystem

Source: Hüsinget al.(2023), the GFI (2020)

8.2 Publications and Patents

The publication analysis for alternative proteins shows an ongoing rise of publications over time, whereas there is a remarkable higher increase since 2018 (Figure 16). The growth of the number of relevant publications in Germany is relatively similar to the world-wide development. Nevertheless, publications in Germany stagnated for plant-based food from 2008 to 2016 where they still increased slightly world-wide. Germany's share of all publications in this field varied a lot over time, but rather increased in recent years to around 4% from 1-2% in the early 2000s.

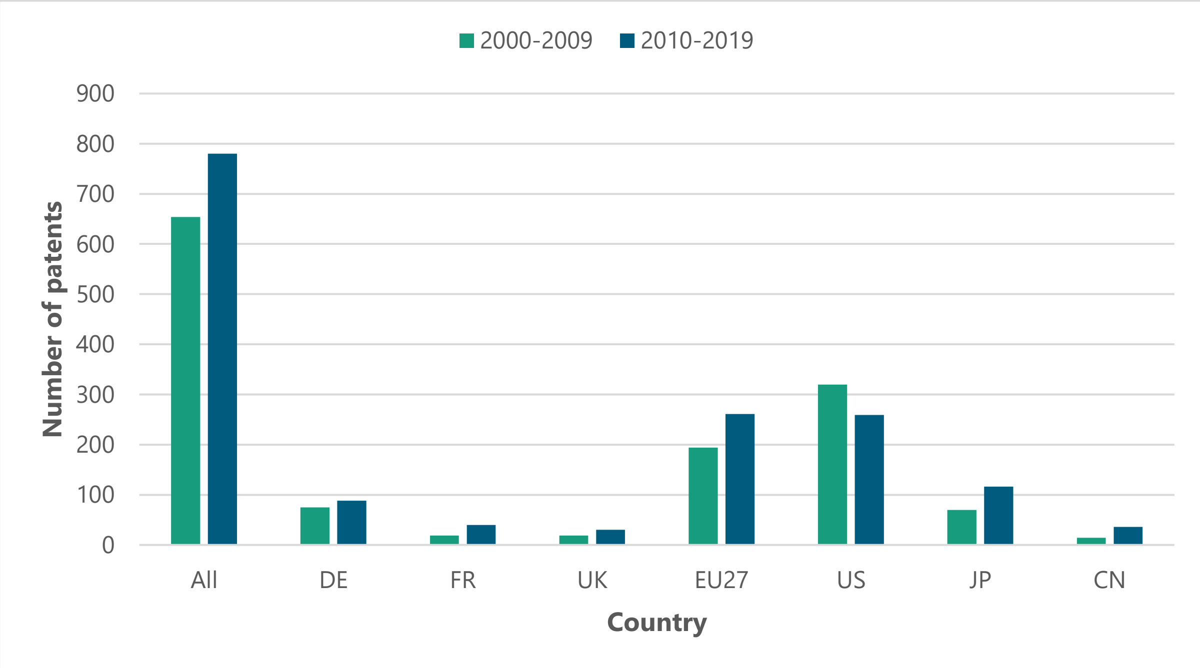
Figure 16: Publications for alternative proteins 2000-2021



Source: Fraunhofer ISI based on Scopus

Regarding patents, overall the numbers increased slightly from 2010-2019 compared to 2000-2009 (Figure 17). While the US was ahead of the EU-27 in the first 10 years of the century they were equal in the recent period. Germany contributes about 35% of this increase in the EU-27 patents in alternative proteins. Therefore, Germany is leading patents in meat alternatives in the EU. While France, the UK and China have generated less than 50 patents each in the recent period, Japan recently managed to increase its number higher than Germany. This substantial rise started in 2018.

Figure 17: Transnational patents for alternative proteins, comparison of 2000-2009 and 2010-2019



Source: Fraunhofer ISI based on Scopus

1.3 Market Outlook

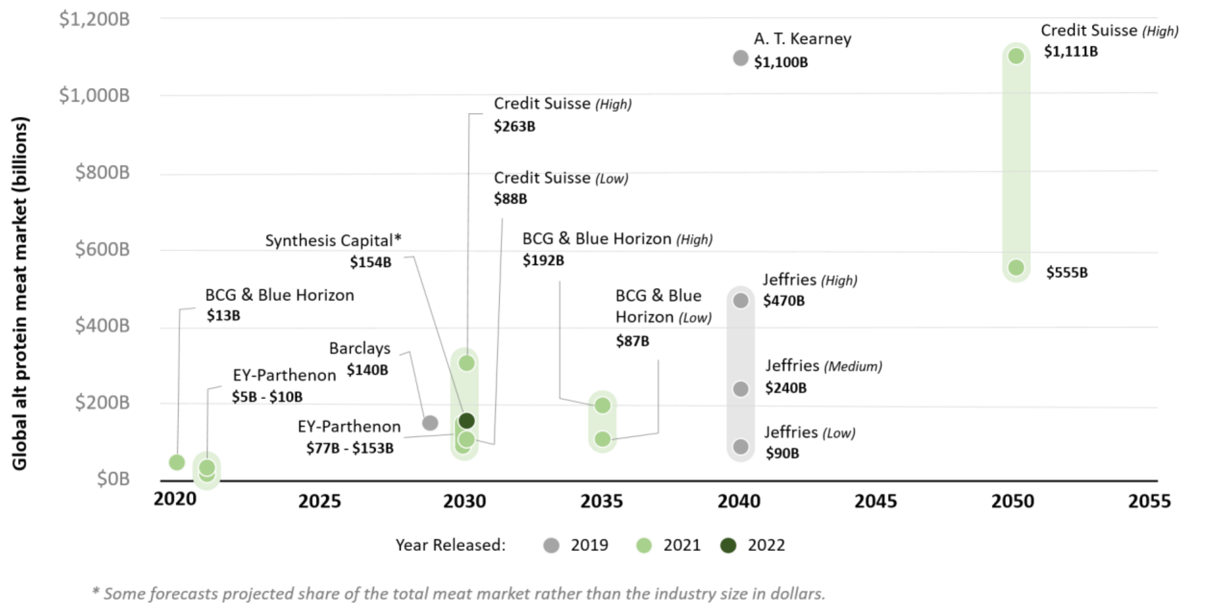
A key challenge in determining market volumes and dynamics for alternative proteins are the varying levels of aggregation given by different sources as well as the differing units of reference. One of the earliest estimates came from Kearney (2019). It dealt with the global market development of meat alternatives. Assuming a compound annual growth rate (CAGR) of 3 % between 2025 and 2040, the authors arrive at a market share of 35 % for cultivated meat and 25 % for vegan meat alternatives in 2040.

Recently, BCG und blue horizon (2021) provided an estimate of the development of the global demand for alternative meat, eggs, and dairy in terms of quantity under three different scenarios (business as usual, pessimistic, optimistic, very optimistic).

Under the Business-as-usual scenario, their calculation expects alternative proteins to attain a market share of about 11 % by 2035. Moreover, even a downside scenario would result in a 10%-market share still. Conversely, under very optimistic assumptions - e.g. regulations like CO_2 taxes or the reallocation of subsidies - a market share of about 22 % seems feasible. According to the authors, plant-based products are going to dominate the alternative protein market with a share of about 71 % (BCG und blue horizon 2021). The United States Department of Agriculture (2020) sees Germany at the forefront of a "Vegalution - Vegan Revolution" in Europe. Likewise, the Smart Protein Project (2021) market review for selected EU Member States and the United Kingdom, found Germany to have the highest growth rate of plant-based alternative protein sales value, i.e. 97 % between 2018 and 2020. While the milk-alternative market stood at around EUR 396 mn, meat alternative sales amounted to about 181 mn. Including products such as Tofu, Statista (2021) computed a sales volume of about EUR 387 mn for 2022 in its its dossier on vegetarian and vegan meat alternatives in Germany.

Various estimations for alternative proteins are summarized in Figure 18.

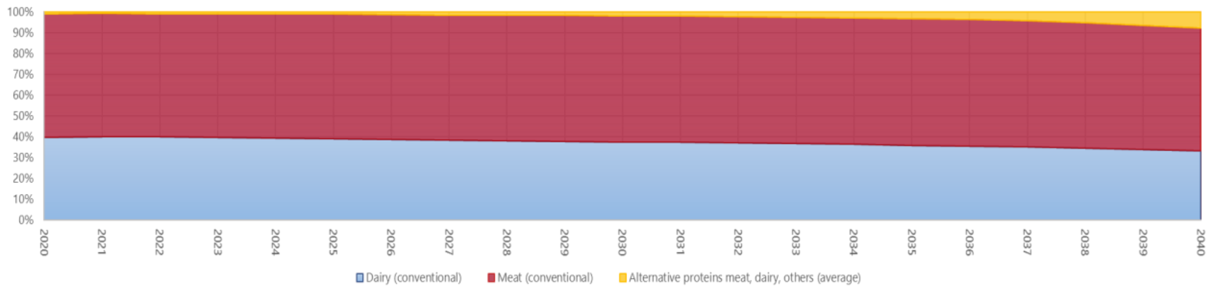
Figure 18: Total alternative protein industry forecasts by year released



Source: see graph

However triangulating different market studies for (i) the category of alternative proteins and (ii) the two most prominent alternative protein products, meat and dairy, and comparing them with the expected development of the conventional meat and dairy markets suggests that alternative proteins will remain a niche market in the foreseeable future (Figure 19). The more so, as the data on alternative proteins used constitute an upper limit, because some studies include products which do not fall under the definition of alternative proteins of this analysis, such as animal feed or tofu, thus increasing the market values.

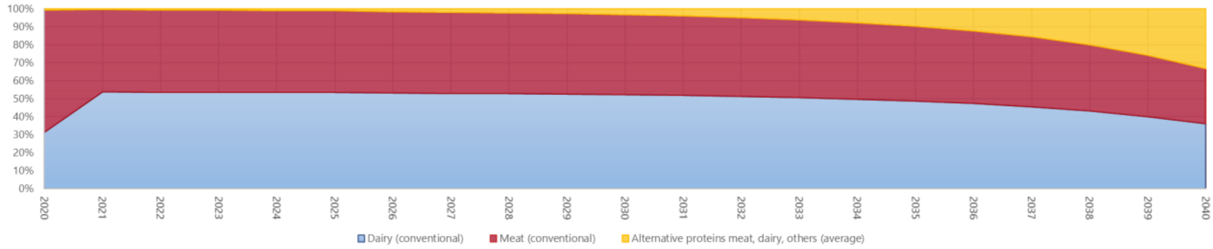
Figure 19: Market forecasts for different types of alternative proteins until 2040, compared to conventional meat and dairy



Source: Own calculation, based on (Allied Market Research 2022a, 2022b, 2021; Fortune Business Insights 2022a, 2022b, 2022c; Future Market Insights 2023; Global Market Insights 2022; Grand View Research n.d.a, n.d.b; Markets and Markets 2021; Meticulous Research 2022; Research and Markets 2022; Statista 2022c; Vantage Market Research 2022; Kearney 2019)

Sensitivity analysis indicates that even under the assumption of shrinking conventional dairy and meat markets at a yearly rate of 5 %, alternative proteins will, ceteris paribus, hold a market share of less than 50 % by 2040 (Figure 20).

Figure 20: Market forecasts for different types of alternative proteins until 2040, compared to conventional meat and dairy using a compound annual growth rate for conventional meat and milk of -5 %



Source: Own calculation, based on (Allied Market Research 2022a, 2022b, 2021; Fortune Business Insights 2022a, 2022b, 2022c; Future Market Insights 2023; Global Market Insights 2022; Grand View Research n.d.a, n.d.b; Markets and Markets 2021; Meticulous Research 2022; Research and Markets 2022; Statista 2022c; Vantage Market Research 2022; Kearney 2019)

8.3 Potential Impact

There remains uncertainty with respect to evaluating alternative proteins' sustainability impacts. In particular, due to their nascent technological state, assessments of cell ag products come at large insecurities. Especially evaluations of the environmental impacts of cultivated meat can only be judged indicative, with huge uncertainties pertaining to the ingredients of the cell-culture medium and the design of the bioreactors for large-scale production. Accordingly, results necessarily depend assumptions, e.g. on whether the used energ are low-carbon, whether envisaged scale-up designs can be met economically (Tuomisto 2022), the referent meat type (e.g. Sinke und Odegard 2021), or the referent unit (e.g. Shanmugam et al. 2023).That is to say, any information about the sustainability of cellular products should be read with utter caution since the social, economic, or more complex ecological impacts of alternative proteins, remain to be determined by future research.

<u>Ecological contribution</u>

Meanwhile there have been several studies, which try to synthesize the ecological impacts of meat alternatives (Santo et al. 2020; Shanmugam et al. 2023; Smetana et al. 2023). However, due to the differing data quality of their sources (e.g. Shanmugam et al. 2023), fine-grained comparisons seem hardly possible. In tendence, however, they suggest an overall sustainability advantage compared to conventional meat, although different types of meat may fare better or less (see Table 8 for an illustration).

Table 8: Land and water use comparison cultivated meat and conventional meat

Product	Land	Land Saving Cultivated Meat (conventional energy)	Water (blue)	Water (blue) Saving Cultivated Meat (conventional energy)
Unit	Area time crop equivalent / kg product		Liter/ kg product	
Beef (beef cattle)	31.6	29.8	258	216
Beef (dairy cattle)	8.8	7.0	115	73

Pork	6.0	4.2	40	-2
Chicken	4.6	2.8	46	4
Cultivated Meat (conventional energy)	1.8	0.0	42	0
Cultivated Meat (sustainable energy)	1.7	0.0	56	14
Tofu	1.8	0.0	27	-15
Meatless	0.2	-1.6	2	-40

Source: Sinke und Odegard (2021)

Whereas beef production is particularly resource-inefficient, poultry and pork fare much better. Similarly, a study on meat alternatives commissioned by the Umweltbundesamt (Jetzke et al. 2019), found them to perform best compared to conventionally produced meat, with 1 kg of soya-based meat alternative equalling up to 1,17 kg $CO_{2\ eq}$, pork emitting 4.1 kg $CO_{2\ eq}$, poultry up to 4.3 kg $CO_{2\ eq}$ and beef as much as 30.5 kg $CO_{2\ eq}$.

What is more, available publications indicate that processed products or cultivated meat have larger impacts on the environment than proteinaceous vegetables, such as pulses (Santo et al. 2020; Shanmugam et al. 2023)[30].

With respect to milk alternatives, there are even less data available. While Silva und Smetana (2022) conclude that plant-based milk was, with exceptions, less resource-consuming than conventional milk, the authors explicitly emphasize the significant limitations of their study, e.g. on the nutritional profiles of plant-based milk. Whereas Geburt et al. (2022) found lower impacts for oat, soy and almond milk compared to conventional milk on a weight basis, this advantage narrowed significantly when using the energy or protein content as the unit of reference. Yet, as the authors excluded fortified products from their analysis, these results are very limited.

Social and economic contribution

As mentioned above, social, economic, or more complex ecological impacts of alternative proteins have not been in the center of empirical verification so far. A recent survey among experts on the impact of meat alternatives on jobs in Brazil, the United States and Europe indicated the potential to create new and higher-skilled jobs. In addition, it suggested that not all meat-sector actors will be affected equally by the spread of meat alternatives, with livestock farmers most likely to be hit in particular (Morais-da-Silva et al. 2022). It seems intuitive to assume the same for the dairy sector.

Table 9 provides an exemplary list of further potential impacts discussed in the literature.

Table 9: Potential sustainability impacts of alternative proteins

Sustainability category	Potential impact	Positve or Negative
Social	Uphold a food culture where „meat" is the prime ingredient of a plate, as no major shift in dietary patterns are induced by meat substitutes	negative

[30] The data is inconclusive with respect to little-processed meat alternatives such as Tofu. While Santo et al. 2020 suggest Tofu to have a lower impact than processed plant-based meat alternatives and cultivated meat in terms of greenhouse gas footprint, they likewise suggest it fares worse than them with respect to land use per gram of protein.

Social	Facilitate small sustainability changes for a large share of the population	positive
Social	Improve animal welfare by decreasing the amount of livestock produced	positive
Social	Reduces public health risks linked to the excessive levels of livestock production, such as antimicrobial resistance or the emergence of zoonotic diseases	positive
Economic	Lead to further centralization in the food value chain as their resource intensity favors larger companies (especially in the case of cellular products)	negative
Economic	Render obsolete animal(-oriented) farming, and thus endangers rural communities[31]	negative
Economic	Lures incumbents into more far-reaching sustainability transitions	positive
Ecological	Reduces ecological risks linked to the excessive levels of livestock production, such as deforestation	positive

Source: Own compilation

8.4 Summary of relevance and suitability for case study selection

In the light of the manifold sustainability weaknesses of our food system, and the significant hesitance of politics to "meddle" with peoples' diets, alternative proteins constitute one lever for sustainability, as they show the potential to save GHG emissions, land, and water and as they address an array of other issues, such as animal welfare.

However, whereas insightful studies have been performed to assess their potentials in detail, corresponding predictions remain subject to significant uncertainty. Inter alia, this is due to the rather low maturity of some products and technologies, to the heterogeneity of product types that make up the alternative protein category as well as due to the broad variance in the products to which they have been compared.

An in-depth cases study on alternative proteins should hence focus on a pre-defined set of specified products for further analysis. In this respect, meat alternatives constitute a particularly salient case. Not only does meat enjoy a particularly firm place in culture (Leroy und Praet 2015). But from a technological point of view, the category also provides products of different degrees of maturity, i.e. plant-based alternatives (rather mature) and cultivated meat (rather nascent), which would allow for nuanced analysis of innovation patterns and economic development. Moreover, there are potential links to model approaches possible as alternative meat alternative diffusion may have a significant impact on these variables

[31] Product portfolios in farming are less flexible than in other sectors because of ecological limitations. In some cases it is not even possible to substitute between different products of the same category, e.g. grassland by legumes. Changing the product portfolio beyond ecological boundaries may cause severe economic, e.g. lower yields/qualities/revenue, and/or other losses, e.g. lower biodiversity.

9 Technology Field Plant Breeding

9.1 Characterization of technology field

9.1.1 Definition and Delineation

Plants are the most important feedstock for the bioeconomy. The provision of sufficient amounts and qualities of plants and plant biomass must be secured in order to meet the demand for e.g. food, feed, fibre, fuel, ecosystem services, landscaping. Plant breeding is the science and practice of the genetic improvement of plants. By plant breeding, the genomes of plants are changed in order to obtain plants with desired characteristics. Desired traits are e.g. yield, nutritional quality, plant disease resistance and stress tolerance. Plant breeding is an iterative process which starts from genetically diverse populations of plants. The genetic diversity can be due to naturally occurring biodiversity, but usually it is created intentionally (e.g. by crossing or mutation). From these populations, plants with the specific desirable traits are selected[32].

9.1.2 Current status and potential future developments

Technologies and technological advances

Each plant breeding program is a cyclical, iterative process. Each cycle consists of three major phases (Ceccarelli 2015):

1) generating genetic variability (e.g. by crossing parent plants with different characteristics, by inducing mutations, by introducing exotic germplasm, or by genetic engineering techniques)
2) identification and selection of promising candidates with improved properties (e.g. by marker-assisted selection, or use of high-throughput phenotyping) and propagating these candidates
3) testing the promising candidates in multi-year, multi-location and multi-environment trials in order to select the superior genotypes.

In the first phase, two major approaches can be distinguished how genetically diverse populations are generated for selection (Ahmar et al. 2020):

- Classical breeding relies on e.g. cross breeding, introgression, polyploidy breeding and mutation breeding. It mainly uses the gene pool of closely related species and varieties
- Transgenic breeding applies genetic engineering and new genomic techniques (Broothaerts et al. 2021) for this purpose. By genetic engineering, genes from other species or engineered genes can be introduced into plants, thus opening the opportunity to exploit a much broader gene pool for plant improvement for human purposes, to improve metabolic pathways and create new ones, and apply synthetic biology. Especially new genomic techniques allow more precise and targeted engineering of plant genomes and genes than classical breeding or genetic engineering. They are especially useful for the targeted introduction of controlled deletions or insertions to inactivate genes, the precise mutagenesis of single DNA bases, or the substitution of small DNA fragments.

In the last decades, both approaches and all three phases of the plant breeding cycle have been empowered by a broad spectrum of different methods and techniques. Their aim is to speed up

[32] https://www.plantbreeding.org/content/what-is-plant-breeding/; accessed 28.3.2023

the plant breeding process, to reduce costs, to enhance the accuracy and precision of genetic alteration, and to increase the success rate of obtaining a new variety with the desired new traits. Among these technological advances are

- Whole genome sequencing. Since the publication of the first plant genome sequence in 2000, 1031 genomes of 788 different plant species and subspecies have been sequenced and published until 2020, and the number continues to grow (Xiong et al. 2022). Knowledge of the genome sequence of a plant significantly enhances the understanding of the biological functions encoded in the genome, the biological basis of traits, and on the evolution and history of modern crop plants. It allows much more rational breeding approaches.
- Marker-assisted selection. In marker assisted selection, a superior candidate is not selected by the trait of interest itself (e.g. disease resistance, stress tolerance), but based on a marker which is linked to this trait. Marker-assisted selection is usually applied in phase 2 of the breeding cycle. It is especially useful for traits that are e.g. difficult or expensive to measure or are expressed late in plant development. The number of relevant markers, especially genetic markers, has increased substantially by knowledge from whole genome sequencing and an improved understanding of the biological and molecular mechanisms and processes underlying traits of interest (Hasan et al. 2021).
- High-throughput phenotyping. The selection of an improved or the best phenotype is a crucial step in the plant breeding cycle, in phases 2 and 3. High-throughput phenotyping platforms allow rapid automated trait analysis of a high number of plants at different development stages. Phenotyping platforms are available for phenotyping in the laboratory under controlled conditions and in the field under natural conditions. They comprise automated sensing (e.g. by different imaging technologies), data acquisition, and data analysis to generate phenotypic data. Laboratory and greenhouse platforms rely on laboratory automation. Field platforms acquire data via drones or satellites which are equipped with the imaging technologies (Jangra et al. 2021).
- Smart breeding supported by bioinformatics and artificial intelligence. The phenotype of a plant (its performance) is determined by its genotype, the environment in which it is grown, and the genotype-environment interaction. Various omics-technologies provide large datasets on e.g. genotype and active genes (transcriptome), plant protein expression (proteome), plant metabolism (metabolome). High-throughput phenotyping platforms and environmental monitoring technologies provide data on the environment and plant behaviour and performance in this environment. Artificial intelligence plays a major role in analysing these large data sets and in integrating them into models for the more precise prediction of phenotypes, thus guiding, monitoring and improving breeding strategies (Xu et al. 2022).

The combination of these methods, either in classical plant breeding or transgenic breeding approaches, remains an essential tool for developing improved crop varieties that meet the demands of modern agriculture. However, it has been estimated that global production would have to be doubled in 2050. This would require an even higher increase in crop productivity per year, around 2 % per year (Xiong et al. 2022).

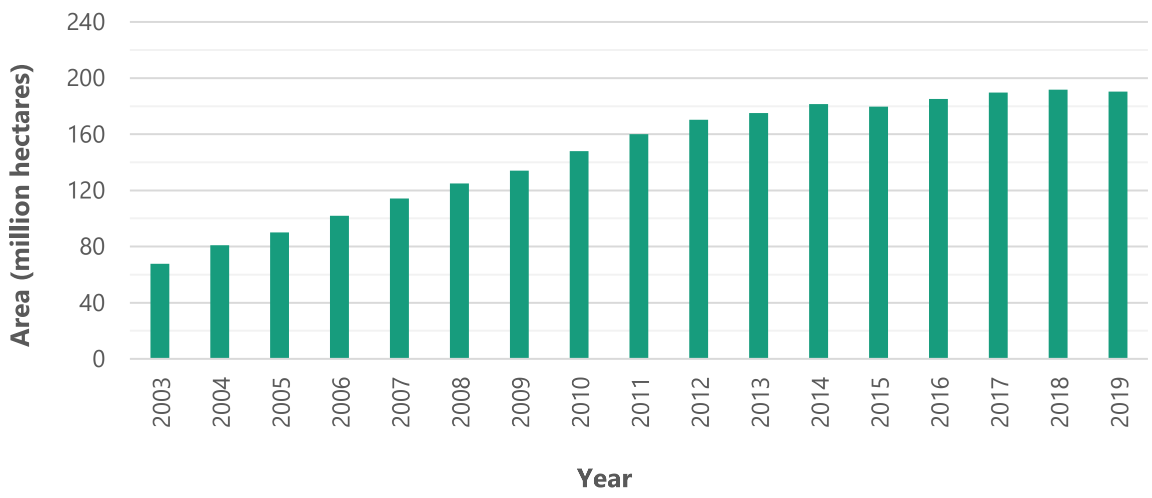
Genetically modified crops

The following information is taken from ISAAA (2019): In 2019, genetically modified crops were grown on 190.4 mio. hectares worldwide (Figure 21). Five countries (USA, Brazil, Argentina, Canada and India) planted 91 % (172.7 mio. hectares) of the global GMO crop area. The USA are clearly leading with 71.5 mio. hectares, followed by Brazil (52.8 mio. hectares) and Argentina (24.0 mio hectares). Other countries which grow more than 1 mio. hectares of GMO crops are Paraguay, China, South Africa, Pakistan, Bolivia and Uruguay. The only EU countries in which GMO crops were grown in 2019 are Spain (107,130 hectares) and Portugal (4,753 hectares). In these countries, insect-resistant maize is grown to reduce losses due to the European corn borer.

Soybeans, maize, cotton and canola are the major GMO crops, accounting for appr. 98 % of the area where GMO plants are grown (Table 10). 75 to 80 % of globally grown soybeans and cotton are GMOs, already approaching saturation of the GMO market. The share of GMO maize and canola in globally grown maize and canola are 31 % and 27 %, respectively (Table 10). Other GMO plants than the "big four" account for less than 2 % of the GMO crop area (1.8 mio. hectares). These are (in descending order of area) alfalfa, sugar beets, sugarcane, papaya, safflower, potatoes, eggplant, squash, apples and pineapple.

The vast majority of GMO crops are herbicide- and insect-resistant crops (45 % of GMO area), followed by herbicide-resistant crops (43 %) and insect-resistant crops (12 %). Crops with other genetically engineered traits are quantitatively negligible.

Figure 21: Acreage of genetically modified crops worldwide 2003-2019



Source: ISAAA (2019)

Table 10: GMO crop area worldwide 2019

GMO crop	Area (mio. hectares)	% of global GMO area	% of global crop area
Soybean	91.9	48	74
Maize	60.9	32	31
Cotton	25.7	13	79
Canola	10.1	5	27
Other	1.8	2	-
Total	190.4	100	-

Source: ISAAA (2019)

Breeding goals

Present breeding goals are to minimize crop losses while maximizing crop yields, rather than increasing acreage to increase cultivation. The most important breeding objective for all crop types is yield increase and yield stability despite climate change and under regional conditions. Yield is also closely linked to other breeding goals, such as disease and pest resistance, nutrient efficiency (e.g. efficient use of fertilizer, high productivity even in nutrient surplus or shortage), and stress tolerance (e.g. drought, weather extremes)[33]. Other breeding goals are more species- or use-specific: optimising cultivation properties, so that the plants are well adapted to agronomic production processes. The breeding goal "quality" comprises e.g. the nutrient composition of fruits, health effects, taste, processing properties etc. For energy plants, increasing the total biomass, and/or the content of oil, sugars or starch are relevant breeding goals.

According to Xiong et al. (2022) climate change has made resilience breeding the top priority in breeding goals. Genetic engineering of crop plants has, up to now, only made a minor contribution to the goals or resilience and disease resistance in commercially grown plants (Pixley et al. 2019).

For further deployment of plant breeding technologies, the following key drivers and barriers arise (Table 11).

Table 11: Main drivers and barriers for further deployment of plant breeding technologies

Drivers	Barriers
Yield improvement by the strategies enlargement of agricultural areas and by application of fertilizers and pesticides has reached or even exceeded sustainable boundaries. As a consequence, improvement of inherent plant properties and performance by breeding gains top priority (Sauter und Zulawski 2022)	Breeding goals are not always aligned with sustainable agricultural practices (e.g. focus on a few varieties vs. agrobiodiversity)
Growing food demand: Plant breeding can increase crop yields and nutritional value to meet demand of a growing world population (Batur und Dedeurwaerdere 2014; Goldman 2021).	Unresolved concerns and conflicts around the use of genetic engineering and new genomic techniques in plant breeding (Zimny et al. 2019), e.g. concerns around safety, health and environmental impact, and ethical considerations
Climate change: Plant breeding technologies can help to develop crops that are more resilient to these changes and better able to adapt to new environmental conditions (Goldman 2021).	Regulation: The regulation of genetic engineering and new genomic techniques varies across different countries and regions (Purnhagen und Wesseler 2021). EU competitiveness might be impeded if other regions apply these technologies.
Pest and disease pressure: Plant breeding technologies can help to develop crops that are resistant to pests and diseases, and reducing the need for chemical pesticides (Batur und Dedeurwaerdere 2014).	Lack of global authorization standards which hinders easy trade of products (Zimny et al. 2019).

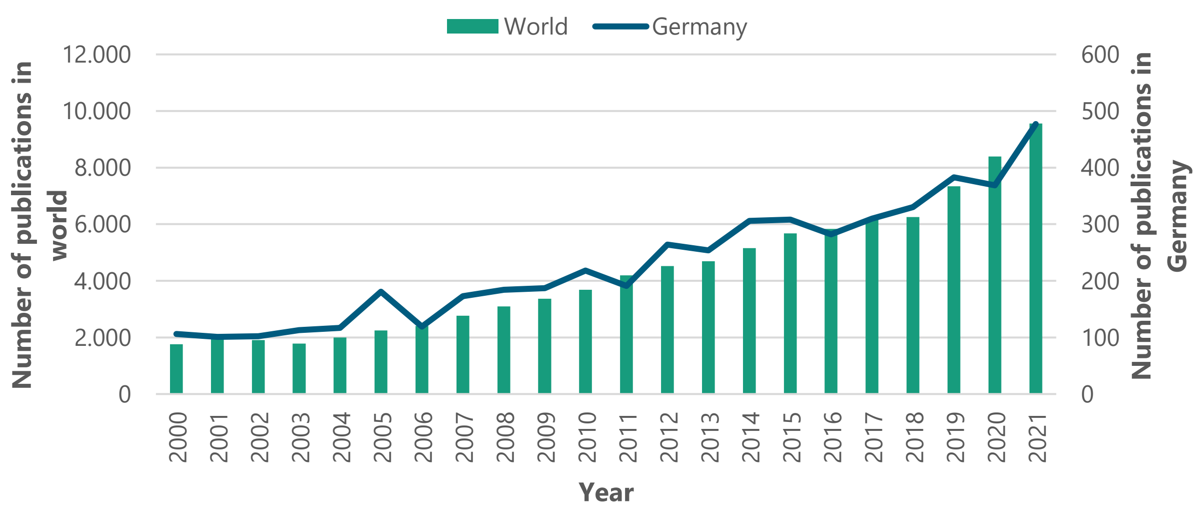
[33] https://www.kws.com/corp/en/media-innovation/innovation/breeding-objectives/; accessed 30.3.2023

Consumer preferences: Plant breeding technologies can help to develop crops with these desired traits, improving the quality and nutritional value of the food we eat while reducing the environmental impact of agriculture (Qaim 2020).	Public perception and acceptance: Public perception and acceptance of genetic engineering and new genomic techniques in plant breeding is low in the EU and can remain a significant barrier to their deployment (Qaim 2020).
Technological advancements: New methods and techniques allow more precise, rational and quicker breeding cycles (Park et al. 2019).	The Farm to Fork strategy goal is to increase organic farming area to 25 % by 2030. However, organic farming legally excludes the use of genetically modified organisms (Purnhagen et al. 2021). Organic farming requires more land than conventional agriculture for the same quantity of food output.
Breeding and seed markets are dominated by very few multinational companies. Breeding strategies largely depend on strategies of these companies.	

9.2 Publications and Patents

From 2005, total global publications on plant breeding have increased progressively (Figure 22). During 2019, there was a stronger growth. Many of these advances differ from German publications. The aforementioned strong growth began in 2020 and followed a decrease. This pattern occurred on multiple occasions in 2006, 2011 and 2016. Germany's percentage of global publications fluctuates between 5% and 6%, with a modest decline beginning in 2020 as a result of greater global growth.

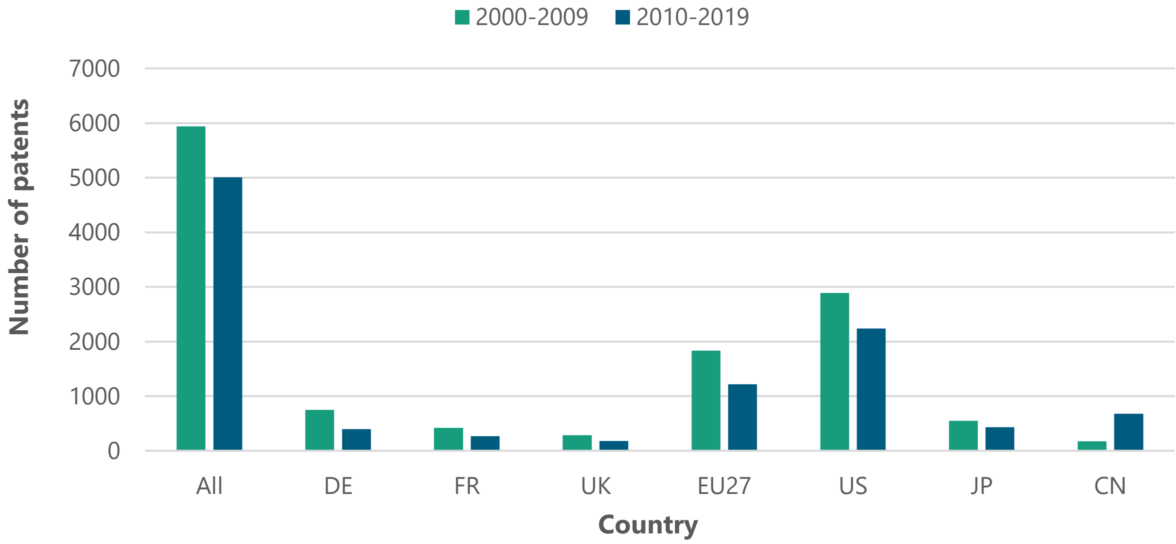
Figure 22: Publications for plant breeding 2000-2021



Source: Fraunhofer ISI based on Scopus

In general, the number of plant breeding patents was lower from 2010-2019 than it was from 2000-2009 (Figure 23). The United States and the EU-27 are the two leading regions, with the United States still in the lead. Germany's average share of patents in the EU is a substantial 36% over time. Despite this, the share is declining. Except for China, every included nation has a greater number of patents in the 2000s than in the recent past. China has nearly quadrupled its patents due to a rapid increase since 2017.

Figure 23: Transnational patents plant breeding, comparison of 2000-2009 and 2010-2019



Source: Fraunhofer ISI based on STN

9.3 Market Outlook

The plant breeding market is expected to reach EUR 32 billion by 2029, growing at a CAGR of 14.1% during the forecast period of 2022 to 2029[34]. The growth of this market is attributed to increasing awareness about the importance of resilient crop production systems and declining costs of genomic solutions. Technological advancements and growing investments from seed companies, along with supportive regulations for molecular breeding, are expected to provide significant growth opportunities for stakeholders in the plant breeding market. However, the high costs involved in modern breeding techniques compared to conventional methods and the lack of standard laboratory infrastructure are expected to hinder the market growth.

The molecular breeding method segment is expected to account for the larger share of the plant breeding market in 2022, with herbicide tolerance as the dominant trait segment. The cereals and grains segment is expected to account for the largest share of the global plant breeding market in 2022. North America is expected to have the largest share of the plant breeding market in 2022, followed by Europe, Asia-Pacific, Latin America, and the Middle East & Africa[35].

The GM crops are not being cultivated or used as food on a large scale in the EU. However, GMOs are being used in the EU, primarily as feed, they are imported from other countries (Zimny et al. 2019). Given that most of the GMOs commercialized up till now were developed by large multinational companies, there are also economic and social concerns related to market power and unequal benefit distribution (Qaim 2020).

The key players profiled in the plant breeding market report include Bayer AG (Germany), Syngenta AG (Switzerland), KWS Group (Germany), Corteva Agriscience (U.S.), Limagrain (France), BASF SE

[34] https://www.meticulousresearch.com/product/plant-breeding-market-5387#:~:text=The%20Plant%20Breeding%20Market%20is,period%20of%202022%20to%202029.

[35] https://precisionbusinessinsights.com/market-reports/global-plant-breeding-market/

(Germany), DLF Seeds A/S (Denmark), Bioceres Crop Solutions (Argentina), UPL Limited (India), Benson Hill, Inc. (U.S.), Equinom Ltd. (Israel), BioConsortia, Inc. (U.S.), Hudson River Biotechnology (Netherlands)[36]. These big companies in Germany may still keep investing on the advancement commercialization of plant breeding technologies. The EU legislation is the main hindrance for deployment of plant breeding technologies based on genetic engineering and new genomic techniques in the EU (Purnhagen und Wesseler 2021).

9.4 Potential Impact

Economic impacts

Plant breeding has played an important role in securing agricultural and horticultural plant production for food, feed, fuel, material and industrial uses. Improved crops may be an important coping strategy for climate change challenges, and a growing world population. However, there are several barriers that could limit their deployment. Especially in the EU and Germany, the regulation of genetic engineering and new genomic techniques, public perception and acceptance of GMOs, health and environmental concerns, limit their adoption. In developing countries, limited capacity and infrastructure for plant breeding may be a barrier (Purnhagen und Wesseler 2021; Klümper und Qaim 2014; Goldman 2021).

Large, multi-national plant breeding companies are dominant in the market and receive the major share of economic benefits (Qaim 2020).

Several reviews of the (economic) benefits of genetically engineered crops have been published. Pixley et al. (2019) summarize the findings of these reviews as follows: "... metaanalyses conclude that genetically engineered maize, cotton, and soybean varieties often outyield and economically outperform their conventional counterparts. The yield advantage is greater for insect-resistant crops under conditions of substantial pest pressure than for herbicide-resistant crops. The advantages have been estimated as 14–40% greater in low-income than in high-income countries. Economic benefits have generally accrued to farmers adopting transgenic crops. It is important to note that some of these studies do not differentiate between yield increases caused by the transgene, differential farmer practices, and seed quality or differences between breeding efforts associated with genetically engineered and non–genetically engineered varieties. Adoption or nonadoption of genetically engineered crop technologies has also resulted in opportunity benefits and costs that are often overlooked. The wide use of genetically engineered insect-resistant crops can suppress a targeted insect(s) across broad regions and increase yield and economic benefits for adopters and nonadopters of the genetically engineered varieties. Unintended costs of adopting genetically engineered crops may also accrue, e.g., those caused by glyphosate-resistant weeds for US farmers. However, these costs should be considered alongside the economic and ecological benefits accrued from genetically engineered crops enabling the use of glyphosate instead of more toxic herbicides."

The future economic impacts depend on the degree of addressing these barriers and ensuring that plant breeding technologies are used in a way that is safe, sustainable, and equitable for all stakeholders.

Ecological impacts

Whether plant breeding has more positive or negative ecological impacts depends to a large extent on the breeding goals, to the diversity of crop varieties that are improved by breeding, and by the

[36] https://www.meticulousresearch.com/product/plant-breeding-market-5387#:~:text=The%20Plant%20Breeding%20Market%20is,period%20of%202022%20to%202029.

agricultural practices for which crops are optimized by breeding efforts. In current dominant agricultural production systems, the focus of plant breeding on a few major crop plants has contributed significantly to the loss of genetic agrobiodiversity and homogenization of agricultural landscapes, leading to the loss of important ecosystem services such as pollination, soil fertility and pest control (Goldman 2021). This has negative consequences for the functioning and resilience of (agro)ecosystems. For example, the widespread use of genetically modified crops with herbicide tolerance could lead to increased use of herbicides, resulting in negative impacts on soil health and water quality[37].

On the other hand, plant breeding is an important option for reducing agronomic inputs such as fertilizers and pesticides, and crops which are more resilient to climate change impacts (e.g. extreme weather events tolerance, disease and pest resistance) can have a stabilising effect on ecosystems and ecosystems services (Goldman 2021).

Therefore, it is important to find a balance between positive and negative ecological impacts to ensure that they are used in a way that is safe and sustainable for ecosystems.

Social impacts

The potential future social impacts of plant breeding technologies are multifaceted and complex, with various potential risks and uncertainties that could impact communities and vulnerable groups. The deployment of genetically modified crops has been a source of debate in the EU, with concerns around issues of food safety, sustainable agriculture and public acceptance (Qaim 2020). Such technologies also contribute to social and economic inequalities by further marginalizing vulnerable communities (Zimny et al. 2019). These effects should be addressed to avoid negative impacts.

9.5 Summary of relevance and suitability for case study selection

While the market outlook for both conventional and molecular plant breeding methods may seem positive, there have been growing concerns regarding the social, environmental, and health impacts of these technologies. The use of conventional breeding methods can result in the loss of genetic diversity and the homogenization of agricultural landscapes. Additionally, concerns over the safety and effectiveness of genetically modified crops are limiting their adoption in some regions, leading to uncertain market prospects for molecular breeding methods. Furthermore, advancements in technology and the increasing demand for crops with specific traits may come at a cost to small-scale farmers and local communities, who may not have the resources or access to these technologies. Overall, while there may be some optimism regarding the market prospects for plant breeding technologies, it is important to consider the potential negative impacts on social, environmental, and health factors. It is crucial to ensure that these technologies are used in a way that is safe, sustainable, and equitable for all stakeholders involved.

Plant-breeding techniques do not present a suitable case study, because of the limited market relevance in the EU due to low acceptance and subsequent regulation.

[37] https://cban.ca/gmos/issues/environmental-impacts/#:~:text=Biodiversity%20Loss%3A%20The%20use%20of,monarch%20butterfly%20in%20North%20America.

10 Technology Field Biopharmaceuticals

10.1 Characterization of technology field

10.1.1 Definition and Delineation

Biopharmaceuticals (or biologics) refer to large organic molecules or cells from biological sources, which are used as drugs with a therapeutic (e.g. hormones, antibodies) or preventive effect (e.g. vaccines). Biopharmaceuticals represent a unique therapeutic paradigm: they are derived from body-own molecules or cells which can only be made available as therapeutic agents in sufficient amounts by biotechnological processes and heterologous expression in genetically engineered organisms. Biopharmaceuticals comprise several chemical classes of molecules. Major classes are recombinant proteins, nucleic acid-based products (DNA, RNA) and genetically engineered cell-based products. Not included are tissue-engineering products (Walsh und Walsh 2022).

10.1.2 Current status and potential future developments

Biopharmaceuticals are pharmaceuticals which are unique to biotechnology: They can only be manufactured economically in sufficient amounts for therapeutic purposes by biotechnological processes by genetically engineered organisms or cell cultures. Moreover, biological knowledge is essential in the R&D process of novel biopharmaceuticals.

The R&D process for biopharmaceuticals comprises the phases of R&D for identification, characterisation and validation of the active agent, its target, its mode of action of the future biopharmaceutical, preclinical research (e.g. toxicity studies), followed by clinical trials phase I-III. Then, biopharmaceuticals have to obtain market approval, in the USA by the Food and Drug Authority (FDA), in the EU by the European Medicines Agency (EMA). Efforts aim at increasing the efficiency of this process, reduce the attrition rate, especially in later (more costly) clinical trial phases, and reduce the time and manpower requirements until approval and market entry.

At the core of biopharmaceutical R&D is scientific-technical knowledge and knowhow gleaned from molecular biology, -omics[38] technologies and data are routinely used for target, active agent and biomarker identification, for elucidation of molecular pathways in health and disease. Rational and irrational molecular design approaches are applied for optimization of the active agent. As biopharmaceuticals are manufactured in living organisms genetically engineered production strains are optimized by genetic and metabolic engineering, using systems and synthetic biology approaches. Artificial intelligence, especially machine and deep learning approaches have been integrated into the R&D process to a large extent in recent years (Smalley 2017; Vamathevan et al. 2019). R&D for drug discovery is carried out in academia, dedicated biotechnology drug discovery SMEs and also large multinational pharmaceutical companies. Because clinical trials and approval processes are cost-intensive and require specific expertise, a usual business model is that large pharmaceutical companies add promising drug candidates to their pipeline which have been developed by SMEs to the preclinical stage or early clinical trials. Preclinical characterisation of promising drug candidates is often outsourced to specialized R&D service providers.

Biopharmaceuticals are a dynamic and innovative segment in the overall pharmaceutical market: In the period 1/2018 to 6/2021, 180 distinct biopharmaceutical active ingredients entered the market in the USA and/or the EU. 85 of them were genuinely novel biopharmaceuticals, 58 were biosimilars,

[38] Th so called –omics technologies stand for genomics, transcriptomics and proteomics, epogenomics and others

31 were me-too products or were newly approved due to incremental improvement of existing biopharmaceuticals, and 15 biopharmaceuticals had been approved elsewhere before. In the USA, appr. 30 % of all genuinely novel pharmaceuticals which were approved between 2018-2021, were biopharmaceuticals (Walsh und Walsh 2022). This underlines the innovative potential of this class of pharmaceuticals.

A major trend are biopharmaceuticals for "personalised" (stratified) or precision medicine: Precision medicine is a healthcare approach that utilises molecular information (e.g. biomarkers from -omics data), phenotypic and health data from patients to group patients who would best benefit from a specific treatment. This also implies that biopharmaceuticals are increasingly targeted to smaller, yet better defined patient groups.

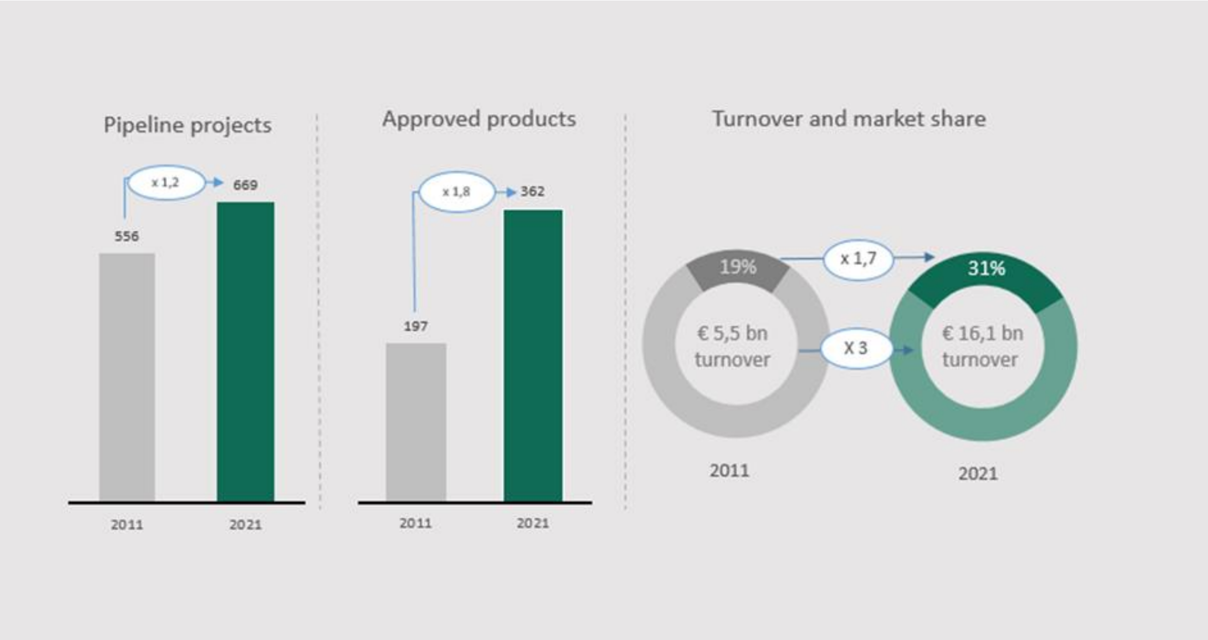
The manufacturing of biopharmaceuticals requires highly complex and sophisticated production processes together with the necessary organisational procedures to ensure product quality, safety and compliance with regulatory standards. The production host systems most often used are mammalian cell cultures, especially due to their ability to do post-translational modification of the biopharmaceutical. "Simpler" biopharmaceuticals which do not require these modifications for their clinical effectiveness are often produced in nonmammalian and less expensive systems, such as bacteria and yeast. Alternative production systems, such as transgenic animals or transgenic crop plants ("pharming"), have been developed in research for decades. However, their role for commercial manufacturing of biopharmaceuticals has so far been negligible, especially by the high requirements for approval of a totally novel production system. A few recombinant pharmaceutical proteins made in whole plants have been granted emergency approval under compassionate use regulations[39].

In biopharmaceutical manufacturing, increased competition as well as the trend towards precision medicine targeting smaller patient groups drive innovations which aim at increasing the speed and high throughput of manufacturing processes, as well as the efficient use of facility space. Therefore, manufacturing process intensification is a priority, as well as the replacement of batch processes by continuous cultures (Cytiva 2021). Moreover, purpose-built stainless steel manufacturing facilities are increasingly replaced by single-use systems (Langer 2022). Digitilization of manufacturing and supply chains, supported by investment in industry 4.0 technology, is ongoing. The Covid19 pandemic has shown significant supply chain challenges, e.g. the procurement of raw materials and essential product components, as well as ensuring the timely delivery of finished goods by logistic companies. Cyberattacks are an emerging threat. As a consequence, making supply chains more resilient (e.g. by outsourcing, regionalizing more, and acquiring second sources) has become more important (Newton 2022).

The use of biopharmaceuticals in clinical application can be derived from approvals and market data. In 2021, 443 individual biopharmaceutical products had market approval in the USA and/or the EU. The reported global sales amounted to 343.3 bn US-$ (Walsh und Walsh (2022);Table 13). 362 of these biopharmaceuticals had market approval in Germany (Lücke et al. 2022 ;Figure 24). They generated sales of 16.1 bn € in Germany in 2021 (table X), representing a share of 31.4 % in overall pharmaceutical sales. Figure 24**Fehler! Verweisquelle konnte nicht gefunden werden.** illustrates the dynamic development of biopharmaceuticals in the last decade in Germany. Internationally and in Germany, biopharmaceuticals have a market share of appr. 30 % in the total pharmaceutical market. Growth rates for sales and market share of biopharmaceuticals are higher than for conventional pharmaceuticals (Figure 24).

[39] https://medicago.com/en/press-release/covifenz/

Figure 24: Development of biopharmaceuticals in Germany 2011-2021



Source: Lücke et al. (2022)

Key drivers and hurdles for biopharmaceuticals are shown in Table 12.

Table 12: Drivers and barriers for biopharmaceuticals

Drivers	Barriers
Biopharmaceuticals have the potential to address unmet medical needs and enable novel therapies	High and increasing R&D and production costs
Continuously rising markets for pharmaceuticals, increasing share of biopharmaceuticals in the total pharmaceutical market	Need to constantly integrate novel approaches and technologies into the R&D process and manufacturing and distribution process (e.g. digitilization, AI, industry 4.0; manufacturing processes flexibly adaptable to smaller biopharmaceutical production volumes, due to targeted therapies)
Increase of biopharmaceuticals for targeted therapies ("precision medicine"), targeting smaller patient populations with higher-value	Increasing awareness of the environmental footprint of the health care sector, putting pressure on reducing the environmental footprint of biopharmaceutical manufacturing and delivery
Increase of biopharmaceuticals for rare diseases, flanked by facilitated market access for orphan drugs	Increasing competition from biosimilars
Well-filled R&D pipelines:	Extremely high costs for several biopharmaceuticals, especially for rare diseases. Public

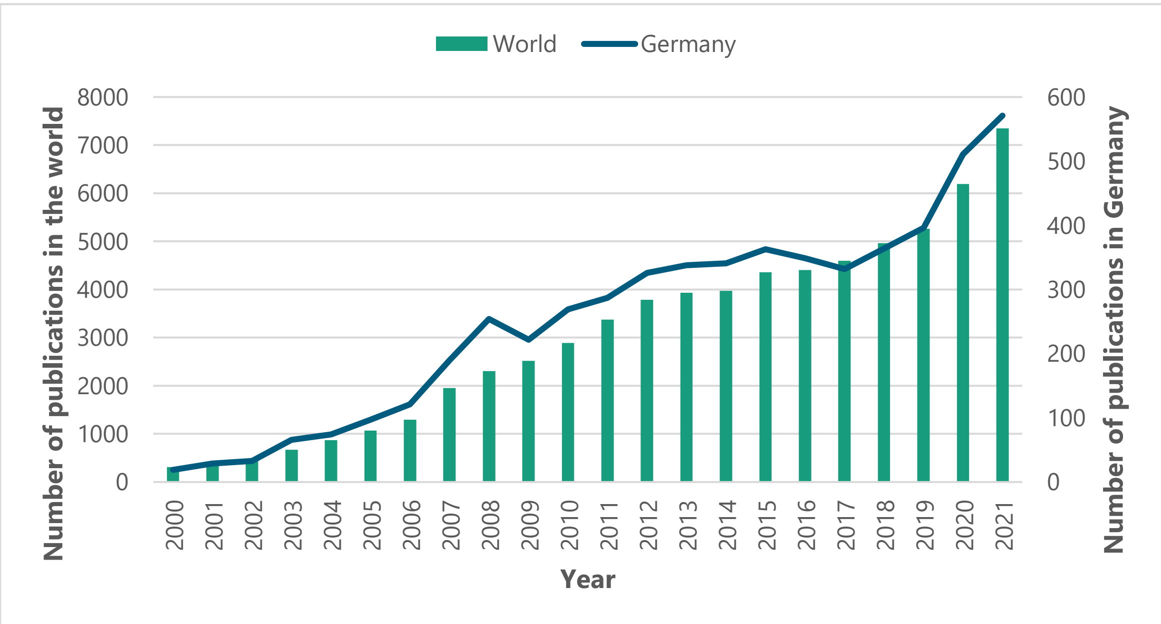
• innovations in major biopharmaceutical classes (e.g. antibody-drug conjugates (ADCs), bi-specific antibodies) • innovations in promising novel biopharmaceutical classes (e.g. Covid19 pandemic as a driver for RNA-based vaccines and therapies; gene and CAR T-cell therapies)	health systems may not be able to provide reimbursements for all newly approved products in the future
Established approval framework for biosimilars/mee-to products	Regulations of national health care systems, especially regarding reimbursement practices and cost containment
Pandemic as an impressive example for the flexibility of the biopharmaceutical sector to respond quickly to an urgent medical need	Vulnerability and lack of resilience of global supply chains
	Emerging threat of cyberattacks
	Shortage of skilled workers

Source: Wydra et al. 2018; Cytiva 2021; Newton 2022; Lücke et al. 2022; Walsh und Walsh 2022; Baltruks 2023

10.2 Publications and Patents

The publication analysis for the field of biopharmaceuticals indicates an ongoing rise of publications with a sharp increase since 2019 (Figure 25). The growth in Germany is aligned to the world-wide development, except from a relatively high increase 2008 and the following the decrease 2009. The same trend happened again from 2015 to 2017 but less varying. Germany's share of world-wide publications over time varied a lot in the 2000s between 6-11% and stabilized in the last 10 years between 7-9%.

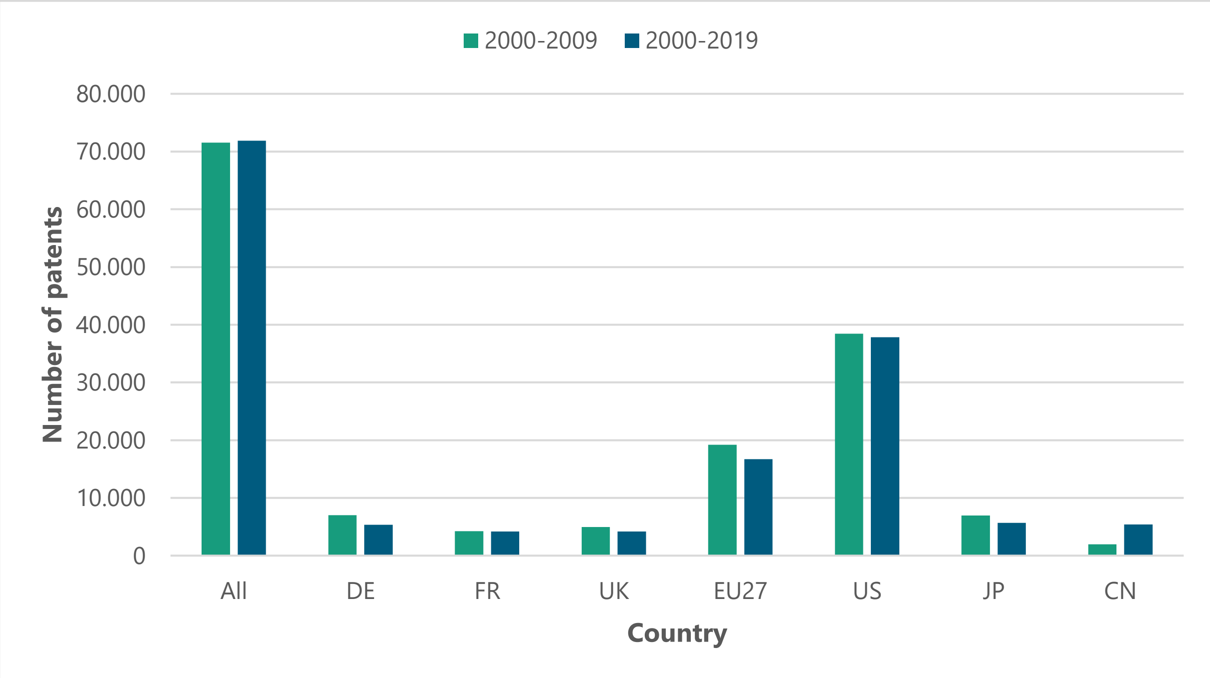
Figure 25: Publications for biopharmaceuticals 2000-2021



Source: Fraunhofer ISI based on Scopus

Regarding patents, the overall development is almost equal with a barely higher number of patents in 2010-2019 compared to 2000-2010 (Figure 26). The US have generated as twice as many patents as the EU-27 over the time. About 36% of the patents in the EU-27 are from Germany on average over time. This share relatively decreased in recent years. Nevertheless, Germany is leading in Europe in the focused period. The development in Japan is similar to Germany. China is the only included country which increased their patents in the last 10 years compared to the 2000s, by two and a half times as much.

Figure 26: Transnational patents biopharmaceuticals, comparison of 2000-2009 and 2010-2019



Source: Fraunhofer ISI based on STN

10.3 Market Outlook

In the last years, the biopharmaceutical market grew considerably. There has been a steep rise in approvals since 2015, this is driven by "genuinely new" biopharmaceuticals as well as by biosimilars and "mee-too" products (Walsh und Walsh 2022). The most dominant product group are recombinant antibodies (Table 13). But with the corona crisis, the mRNA vaccines cormirnaty (Pfizer/Biontech) has become the top-selling biopharmaceutical in 2021, Spikevac (Moderna) is in third position accotding to market data (Walsh und Walsh (2022) .

The growth and increasing importance of biopharmaceuticals compared to the – still growing - overall market is likely to continue, as Figure 27 indicates for the world-wide development. This is because of the strong innovation pipeline and the still increasing importance of biosimilars (Troein et al. 2021).

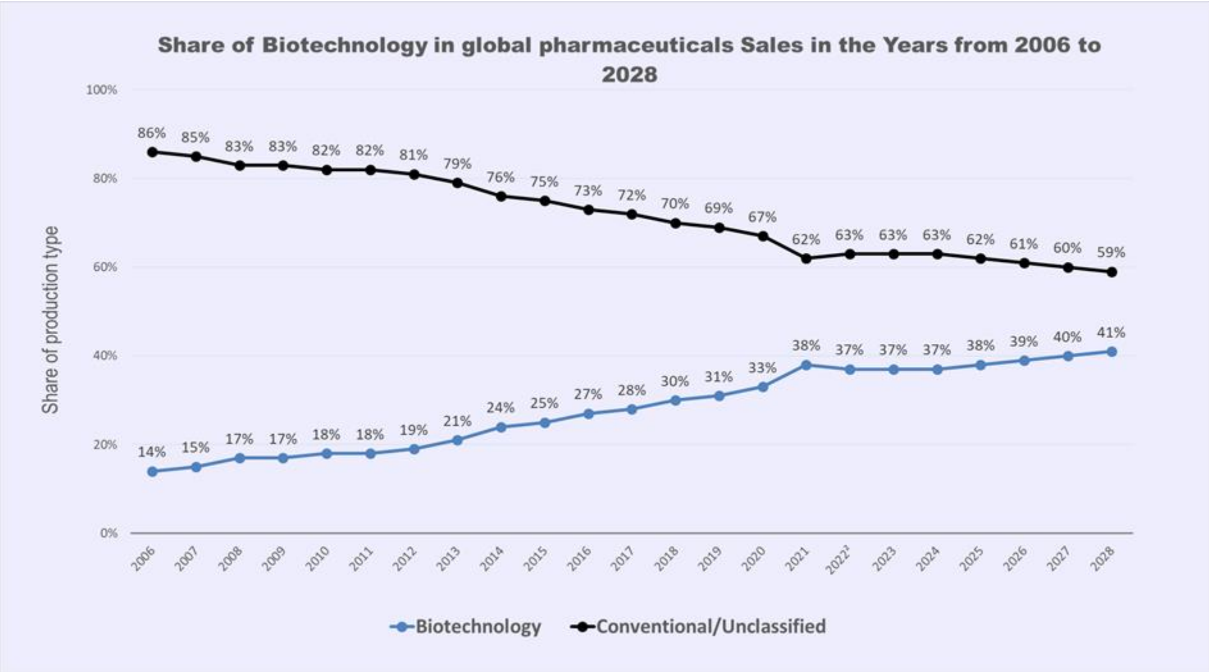
In Germany, the market for biopharmaceuticals has usually grown more than 10 % per year exceeds the total growth of pharmaceuticals. As shown in Figure 24, the turnover with biopharmaceuticals in Germany has more than tripled between 2011 and 2021 (Lücke et al. 2022).

Table 13: Biopharmaceutical global sales values in 2021

Biopharmaceutical category	Reported sales value ($ billi-on)
Originatora recombinant proteins: mAbs	217.3
Originator recombinant proteins: non-mAbs	53.6
Covid vaccines (Comirnaty and Spikevax)	54.5
Biosimilars	11.1
Nucleic acid and engineered cell based	6.8
Total value	343.3

Source: Walsh und Walsh (2022)

Figure 27: Biopharmaceuticals share of the world-wide pharma turnover from 2006-2028



Source: Evaluate (2022)

Within the biopharmaceutical market segment, there is competition between (still) patent-protected biopharmaceuticals and biosimilars. A biosimilar is a biological medicine highly similar to another biological medicine already approved in the EU (called 'reference medicine') in terms of structure, biological activity and efficacy, safety and immunogenicity profile (the intrinsic ability of proteins and other biological medicines to cause an immune response). However, a biosimilar is not regarded as a generic of a biological medicine. This is mostly because the natural variability and more complex manufacturing of biological medicines do not allow an exact replication of the molecular micro-heterogeneity. The EU has established a framework for the approval of biosimilars. The EMA approved the first biosimilar in 2006[40]. Biosimilars usually reach high market shares for the treatment of a given disease, leading to intense competition with the original biopharmaceutical. The intensity of this competition depends to a large extent on the reimbursement regulations and practices in national health care systems. Biosimilar prescriptions bear the potential of signifi-

[40] https://www.ema.europa.eu/en/human-regulatory/overview/biosimilar-medicines-overview

cant cost savings in reimbursements and thus improved patient access to treatment with biopharmaceuticals. In the past decades, the biosimilars market has been dominated by European players, with generics manufacturers like Sandoz, Ratiopharm and Hexal leading the first wave of biosimilar development, alongside global players like Teva and Cipla. Now, other regions and new players enter the biosimilar market. It is not yet clear to which extent they will serve their local market (e.g. Brazil, India), or also compete in the European market (Troein et al. 2021).

Biopharmaceuticals are a segment with very high value added, and highly industrialized countries have an advantage in competition. This is because location factors like highly skilled people and the existence of regulatory settings and control that fulfil global requirements also for potential exports. Germany has a rather strong position in research and development, but plays also a leading role in the production of biopharmaceuticals. 39 different active substances approved in the EU are produced in Germany, which is the highest number for the production of biopharmaceuticals in Europe.[41] For a long time, Germany also possessed the second largest fermentation capacity in the world behind the U.S. However, according the latest available information for 2018, South Korea has surpassed as Germany in fermentation capacity for biopharmaceuticals. There are various concerns regarding the future competitiveness and development of the biopharmaceuticals in Germany, e.g. because of the rather limited number of firms (e.g. compared to France, UK) and low presence of venture capital (March-Chordà und Yagüe-Perales 2021). Moreover, the gap between R&D expenditures in the U.S. and the European countries has risen enormously (Wilsdon et al. 2022).

10.4 Potential Impact

Compared to other bio-based industrial products, biopharmaceuticals are extremely high-value and very low-volume products, which implies the following impacts.

Economic contribution

The economic impact of biopharmaceuticals mainly results from direct value added and employment in the biopharmaceutical industry and to certain extent by indirect effects throughout the value chain and by an increased wealthy workforce. While the number of firms has grown a bit in the last decade, the number of employed persons related to biopharmaceuticals has risen from 28.000 in 2011 to 46.000 in 2021 in Germany (Lücke et al. 2022).

While it was often claimed that value creation does not occur in Germany with the case of Covid-19 vaccines there has been a recent demonstration for production in Germany. With the most recent discussion on European technological souvereinity and resilience it can be assumed that the trend towards relocating production capacities from Europe to non-European countries will slow down or even be reversed in the future.

Environmental Contribution

Awareness has risen internationally that the healthcare sector is responsible for a substantial share of resource consumption and greenhouse gas emissions (Karliner et al. 2019; Lenzen et al. 2020). In Germany, this amounts to appr. 5 % of the total German resource consumption (2016) and greenhouse gas emissions (Ostertag et al. 2021). 75 % of the greenhouse gas emissions of the EU health systems are released indirectly along the supply chain of pharmaceuticals, medical and other products (Karliner et al. 2019). Although no data are available which share of resource consumption and climate gas emissions can be attributed to the pharmaceutical industry in general and to biopharmaceuticals in particular, there is an obvious need for improving current practices. Since 2005, the

[41] https://www.vfa-bio.de/vb-de/vb-englische-inhalte/biotech-location-germany

authorisation of a human pharmaceutical product requires an environmental risk assessment. However, if potentially undesirable effects on the environment are identified, this remains largely inconsequential for the authorisation (Baltruks 2023). The European Commission has proposed to revise this aspect (among others) in the EU pharmaceutical legislation so that the environmental impact of medicine production is in line with the objectives of the European Green Deal (European Commission 2023).

Concerning environmental impact, less land related effects are relevant as in other fields of the bioeconomy. But, potential effects occur in CO_2 emissions for energy, use of water, produce hazardous waste in the production process or the use of plastics in logistics. In general, biopharmaceutical manufacturing processes have a significantly higher process mass intensity (PMI)[42] than processes for making conventional pharmaceutical ingredients: An average conventional pharmaceutical production process has a PMI of 100 to 200 kg/kg, while an input of 7,700 kg has been estimated to produce 1 kg of a recombinant antibody (Kokai-Kun 2022). For the biomanufacturing process, especially water is the single greatest contributing factor to the environmental impact. Water usage in biopharmaceutical production may be >100-fold higher of that used in small molecule manufacturing. A typical 20,000-L batch-based production facility may need more than 5.5 million litres of water in a year, especially for downstream product purification processes (Kokai-Kun 2022). The pharmaceutical industry has only started to address its environmental footprint (Okereke 2021).

Social Contribution

The main potential value is the increase of health and well-being. The effects of biopharmaceuticals cannot be assessed in general and the additional use of a large quantity of innovation/new products discussed for decades. But it can be stated that biopharmaceuticals already dominates in terms of turnover e.g. for immunology or sense organs, and almost presents half of the turnover for oncology and metabolism (Lücke et al. 2022). Recently, higher attention has been given to vaccines, as for Covid-19 with all developed by biotechnological methods. During the pandemic there has been an impressive demonstration of how rapidly the biotech sector could respond to an urgent need in a highly flexible way. However, it remains to be seen in how far this capacity can be maintained also under non-pandemic conditions.

10.5 Summary of relevance and suitability for case study selection

In this sector, biotechnology and biological resources have gained tremendous importance and transformed the sector. Biopharmaceuticals are a completely new kind of therapeutics for unmet medical needs, with potentially better health effects. Economically, biopharmaceuticals contribute significantly to high-value added, growth and employment in the pharmaceutical industry. Germany has a rather strong position in biopharmaceuticals, but there is strong global competition.

Concerning the consideration for a case study, it has to be remarked that it is for a long time under discussion to which extent biopharmaceuticals should be included in definitions of the bioeconomy or not. Biopharmaceuticals are manufactured in biotechnological production processes with living organisms from biogenic resources and the underlying scientific knowledge and technological knowhow is of high importance for other sectors as well. This may justify their inclusion.

[42] Process mass intensity (PMI) is a metric for the efficiency of a manufacturing process: This metric assesses the total mass input in kilograms for a process needed to make 1 kg of output material.

The biopharmaceutical industry is rather well documented in terms of indicators regarding innovation and economics and therefore enables to visualize the important contribution of biological resources and knowledge to the entire economy. A case study can provide more insights in the economic contribution of biotechnology and bioeconomy as well as to assess innovation indicators and innovation patterns.

11 Technology Field Agriculture 4.0

11.1 Characterization of the technology field

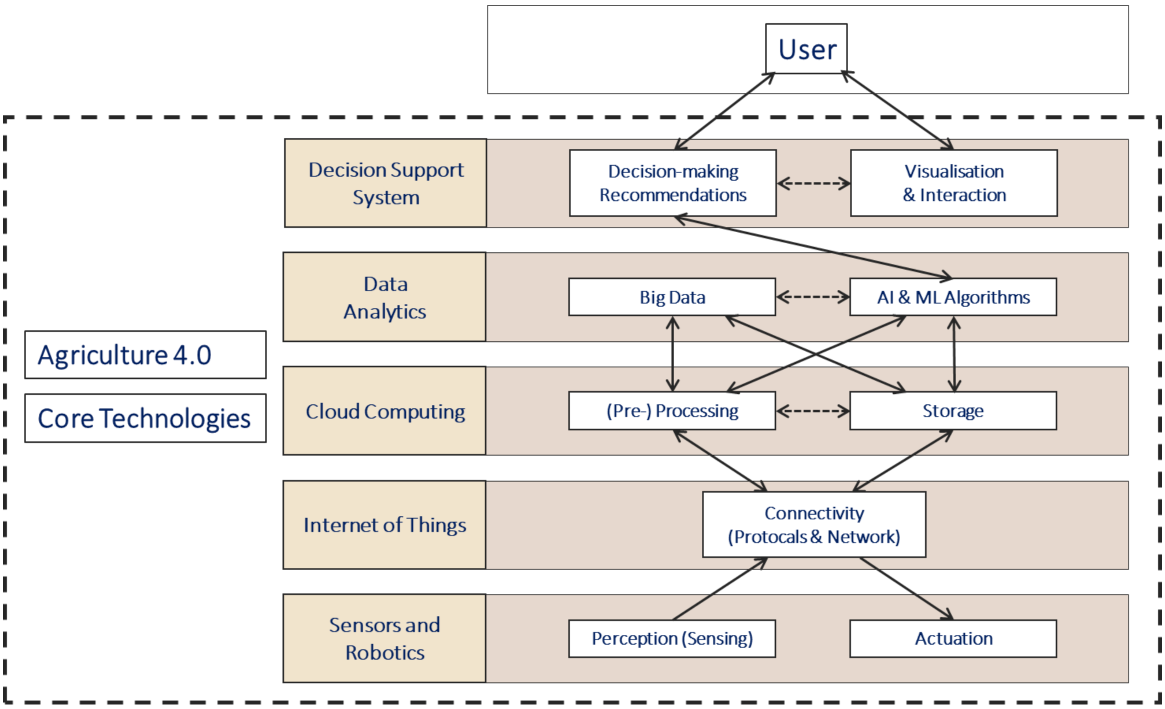
11.1.1 Definition and Delineation

Agriculture 4.0, also termed smart agriculture, smart farming, or digital farming (Aceto et al. 2019), represents the adoption of new digital technologies, such as the Internet of Things (IoT), big data, cloud computing, advanced robotics, and Artificial Intelligence (AI) to optimise the agribusiness production chains in the agricultural sector (Mühl und Oliveira 2022). The adoption of these technologies aims to increase agricultural productivity, improve resource use efficiency, and reduce the environmental impacts of agriculture.

11.1.2 Current status and potential future developments

The agricultural sector has been already adopting digital innovations such as precision agriculture, remote sensing, robots, farm management information systems, and decision support systems. Recent advancements, such as cloud computing, IoT, big data, block chain, robotics and IA navigate the digital transformation in the agricultural sector especially in the recent years (Lezoche et al. 2020). The core technologies of Agriculture 4.0 can be specified as: sensor and robotics (includes perception and actuation functions, depending on the requirements of the system), IoT (for data communication), cloud computing (for data storage and processing), data analytics (includes big data and AI-based methods for data analysis) and decision support system (for data visualisation, recommendation functions and user interaction) (Araújo et al. 2021c). An illustration of the data flow between these technologies is presented in Figure 28.

Figure 28: Data flow between the core technologies of the Agriculture 4.0



Source: Araújo et al. 2021c

However, some of these technologies are placed in a position to improve means and innovations in agri-food systems, but the Agriculture 4.0 seems to still be limited to a few innovative farms

(Klerkx und Rose 2020). Balafoutis et al. (2020) classified these technologies based on the technology readiness level (TRL), and showed that the majority of the relevant scientific papers lies at TRL 5. The maturity level of most Agriculture 4.0 technologies is still relatively low, with most being stuck at the pilot stage under a controlled environment (Araújo et al. 2021c).

Kernecker et al. (2020) reported that farmers in the EU perceive new digital technologies in agriculture useful, but they are still not convinced of its potentials. On the other hand, tech developers seem to be more convinced of assets and potentials of the new digital technologies in agriculture in the EU. Nonetheless, agricultural industry is making considerable progress globally in the context of the implementation of new digital technologies especially in US and China (Araújo et al. 2021c). In the EU, still a little progress has been made in advancing smart agricultural systems beyond the concept and prototype levels to the commercial level (Araújo et al. 2021c). Hence, there are major driving and restraining factors affecting further adoption and application of emerging digital technologies in agriculture (Table 14).

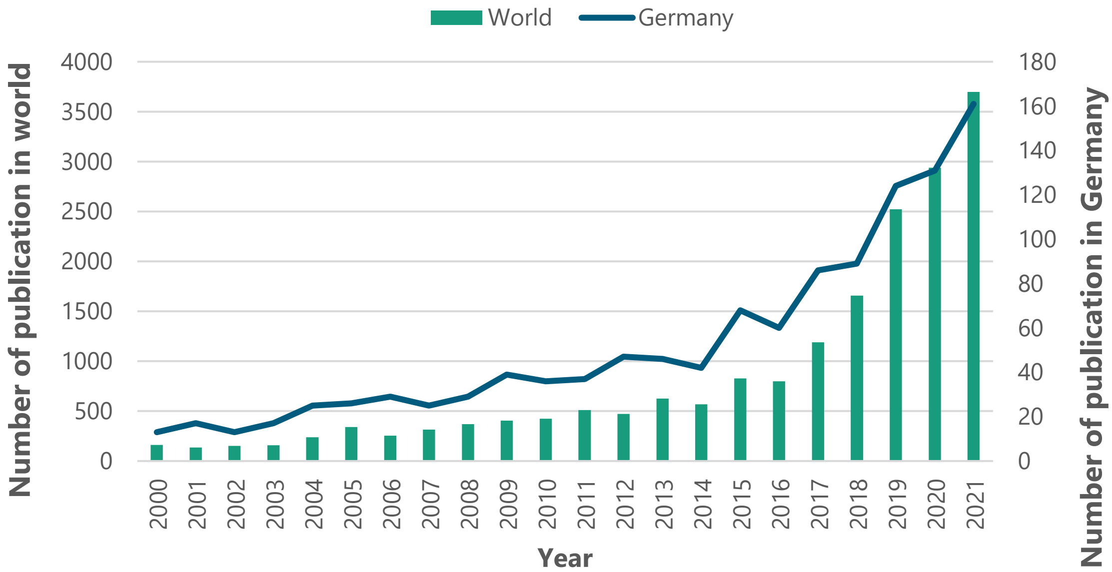
Table 14: Drivers and barriers for development of agriculture 4.0 worldwide

Drivers	Barriers
Population growth and increasing food demand about 60–70% between 2005 and 2050 (Klerkx und Rose 2020)	High costs of Agriculture 4.0 technologies (Klerkx und Rose 2020), and scepticism toward economic returns (Balafoutis et al. 2020)
Recent technological advancements by providing new business operations	Information deficits (Kernecker et al. 2020), and technical, social, and legal barriers related to collecting, storing, and transferring data (Balafoutis et al. 2020)
Necessity for maximizing productivity of agricultural systems involving crop and livestock farming (Araújo et al. 2021c)	Lack of technical skill requirement and low user acceptance especially in rural areas (Lezoche et al. 2020)
Increasing farmland loss and freshwater scarcity, and environmental degradation (Lezoche et al. 2020)	Difficulties in integrating technologies from the most diverse areas of knowledge (Mühl und Oliveira 2022)
Necessity for monitoring of agri-food systems and certification of products	Small scale of farm lands

11.2 Publications and Patents

The publication analysis for the field Agriculture 4.0 indicates a growing rise of publications over time particularly since 2016 world-wide (Figure 29). The total number of scientific publications in smart farming and digital agriculture have increased to about six times between 2011 and 2020. This reflects the substantial progress in emergence of new digital technologies in the agricultural sector. The growth in number of relevant publication in Germany is fairly aligned with the worldwide trends. Germany's share of world wide publications has fallen from around 10-12% in the early 2000s to around 4-5 % in the early 2020s.

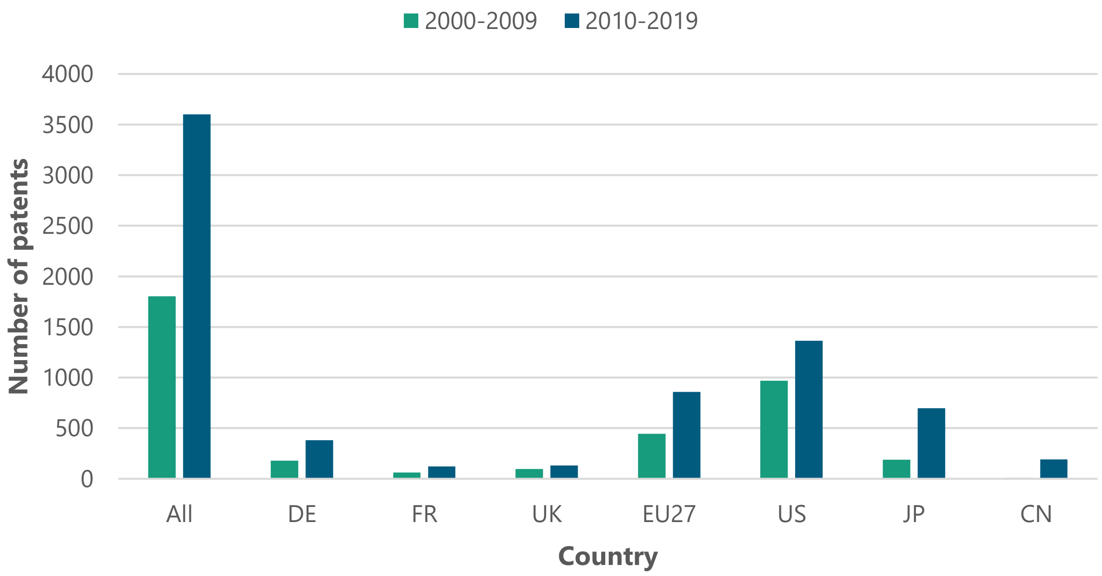
Figure 29: Publications for Agriculture 4.0 2000-2022



Source: Fraunhofer ISI based on Scopus

Concerning patents, the number of patents in 2010-2019 nearly doubled compared to 2000-2009 (Figure 30). The US is leading, applying for appr. twice the number of patents compared to EU-27. Germany generated about 45% of the EU's patents in the recent decade. Germany is leading in terms of patents in the EU. After US, Japan is the second single country with a higher number of patents. China, UK and France are quite behind Germany in terms of number of patents in digital agriculture. Additional patent analysis (graphs not shown) show a growing rise in the number of patents in digital and smart agriculture since 2014.

Figure 30: Transnational patents for digital agriculture, comparison of 2000-2009 and 2010-2019



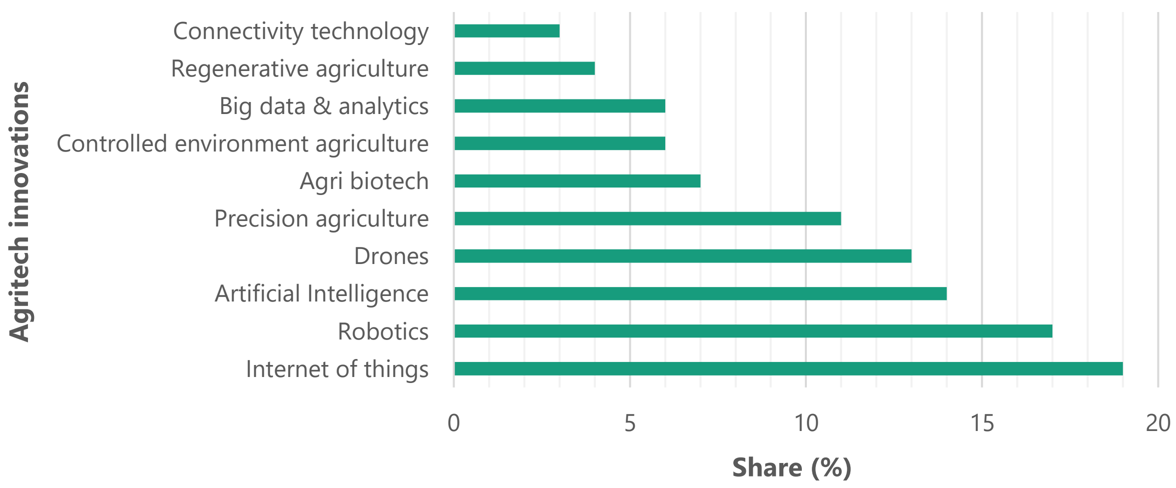
Source: Fraunhofer ISI based on STN

11.3 Market Outlook

The value of the global Agriculture 4.0 market was about EUR 7 billion in 2020, 30% of which is generated in the EU (MarkNtel Advisors 2021). The EU has already acquired a majority market share in recent years and it is projected to witness exponential market growth in the coming years (2021-26). The size of the agricultural workforce is expected to decline at 1% per year, reaching 7.9 million workers in 2030[43] and, in turn, result in the rapid adoption of digital technologies by farmers and mounting automation in the agricultural sector to reduce the human workforce and surge crop productivity (MarkNtel Advisors 2021). Still, slow adoption of digital technologies by small farmers especially in remote and rural areas is a challenge.

Internet of Things (IoT) is the most prevalent agricultural tech innovation of 2022. IoT is a sensor that can monitor crops in real-time and offers farmers insights into crops that would have previously had to be collected manually. Robotics and artificial intelligence are the second and third most influential AG tech innovations of 2022, respectively (Figure 31).

Figure 31: Share of leading agricultural technology innovations as of 2022



Source: StartUs Insights 2022

Moreover, the growing number of high-tech startups in the EU together with the increasing popularity of drones in farming, and massive investments in the agricultural sector by the public and private investors are expected to enhance the market size of digital agriculture and create opportunities for leading countries such as Germany in the EU during 2021-26 (MarkNtel Advisors 2021).

Agriculture 4.0 is expected to changing the job market and the required skills in agriculture, as well as the business models of agri-food enterprises. Countries with a highly educated population, low energy costs, and having governmental support to engage public-private partnerships will eventually grow into leading the Agriculture 4.0 (Clercq et al. 2018). Germany as one of the leading powers on Europe's market, may play a key role for introducing and transferring new digital technologies in agriculture across the EU and beyond.

[43] https://agriculture.ec.europa.eu/news/eu-agricultural-outlook-2020-30-agri-food-sector-shown-resilience-still-covid-19-recovery-have-long-2020-12-16_en

11.4 Potential Impact

Although the Agriculture 4.0 may promote more sustainable agricultural practices and food security, it may have several adverse social, environmental, and economic impacts as well. Further advancements in digital technologies in agricultural sector may leverage the access to technology, land, and capital among different countries and continents, the marginalisation of people and food insecurity, environment pollution, and other related aggravating factors (Mühl und Oliveira 2022).

Economic contribution

Further adoption and application of digital technologies in agricultural sectors are claimed to have various economic impacts in the coming decade, including (Araújo et al. 2021c; Lezoche et al. 2020): (1) Improved operational efficiency: lower production costs, higher productivity and yields, efficient use of resources and farming inputs, and less manual labour required, (2) Lower transaction costs, better decision-making and more efficient market prices, (3) Emergence of new circular business models and cooperation opportunities in agricultural sector, (4) Rise of data economy business models which indicate the share of benefits to everyone in the value chains, and (5) high investment costs into public infrastructure (satellites, high speed internet) and farm equipment.

Ecological contribution

The major potential environmental impacts in the application of Agriculture 4.0 are an overall reduction of agricultural inputs (e.g. fertilizers, pesticides, and irrigation water) (Balafoutis et al. 2020), reduced farm and food wastes due to the enhanced traceability and knowledge-based decision systems, reduced ecological footprint of agricultural practices and logistic (Lezoche et al. 2020).

Social contribution

The adoption of Agriculture 4.0 is expected to eliminate the need for significant amounts of agricultural labour, in the future there may be fewer economic opportunities for those who live in rural areas and keep using conventional farming practices. As a consequence, further applications may exacerbate inequalities in the distribution of wealth in rural areas (Sparrow und Howard 2021). In opposition, innovative digital agriculture has a substantial potential to contribute in improving animal welfare and production of healthy food for the growing population (Lezoche et al. 2020).

11.5 Summary of relevance and suitability for case study selection

Agriculture 4.0 aims to increase the productivity of agricultural systems, improve quality and accessibility of agricultural products, reduce food loss and waste, optimize the use of natural resources and reduce the environmental impact in the coming years. There is a growing trend on adoption of emerging digital technologies especially AI-based applications, sensors and robotics, Internet of Things, cloud computing, data analytics and decision support system in the agricultural sector.

Despite several advantages that the realisation of Agriculture 4.0 could bring, there are still several open issues and challenges that may hinder successful adoption of the digital technologies in agriculture. There is no all-encompassing data and information available on the extent of various applications of digital technologies in agricultural sector. Therefore, it makes estimations of potentials difficult. Agriculture 4.0 is often considered to benefit mainly large scale, technology intensive and specialized farms, but not smaller ones. Another issue is related to scepticism of farmers toward adopting such technologies because of usage complexity, high investment costs and uncertain economic returns. Agriculture 4.0 is not a panacea, particularly in the developing countries, to address food security, but it may rather improve productivity of biomass production and efficiency of resource use to a certain extent.

There is a considerable prospect to further deploy specific streams such IoT, robotics and AI applications and farm waste management in real time. This will offer opportunities to react more quickly to changing conditions in multiple stages of bio-based value chains. Given the rapid growth and innovation in digital agriculture, AI has the ability to optimize resource use, enhance decision-making, and enable innovative solutions throughout different stages of the agri-food systems. Such analysis may enable informed decision-making and targeted strategies for AI integration across the agri-food systems, ensuring sustainability and competitiveness.

12 Technology Field Biotechnology

12.1 Characterization of technology field

12.1.1 Definition and Delineation

Biotechnology is the application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services (OECD 2018). It comprise DNA/RNA, Proteins and other molecules, cell and tissue culture and engineering, process biotechnology techniques, gene and RNA vectors, bioinformatics, and nanobiotechnology.

Biotechnology has overlaps with Life Sciences. There is no precise and commonly applied definition of Life Sciences, but the term is habitually used to encompass all activities from the biotechnology, medical device and pharmaceutical sector with regard to human or animal health. From a technological perspective, Life Sciences are broader than biotechnology, because also other technologies are used. From the application perspective, biotechnology is much broader, because it goes well beyond health applications. Biotechnology is considered a key enabling technology for the bioeconomy. It is especially relevant in the conversion of biomass by bioprocesses (e.g. fermentation, enzymatic processes) (Haaf et al. 2020).

12.1.2 Current status and potential future developments

While concepts and visions for the bioeconomy differ regarding the importance of technological innovation (Hausknost et al. 2017), especially from an industry perspective biotechnology is often considered as the key technology for the bioeconomy. Biotechnology enables new products, processes, services and technologies for a wide range of industries, such as pharmaceuticals and healthcare, agriculture, chemicals (incl. cosmetics etc), plastics, food, and others.

While biotechnology has a long history and has evolved as high-tech for decades, still considerable developments are being achieved. It is considered as the research-intensive and innovative segment within the bioeconomy (Haaf et al. 2020). It is expected that major disruptions are likely to come, e.g. (Wydra et al. 2021a):

First, new cross-cutting technologies have emerged and comprise among others analytical techniques, which are used to probe biological systems and deepen our understanding of their components and functions, as well as tools to engineer these biological systems on demand for desired functions. In genetic engineering, now novel tools (precision genome editing, synthesis and assembly of long DNA fragments, modular cloning systems) are being improved which enable precise, defined alterations of very large DNA fragments, even genomes. A major innovation push is expected from the convergence with digital technologies and artificial intelligence. They are indispensable for analysing and interpreting the vast amount of biological data generated by modern analytical techniques, by complementing and enhancing the established "wet lab" approaches with in silico modelling, and by supporting the digitalisation of the bio-based industry.

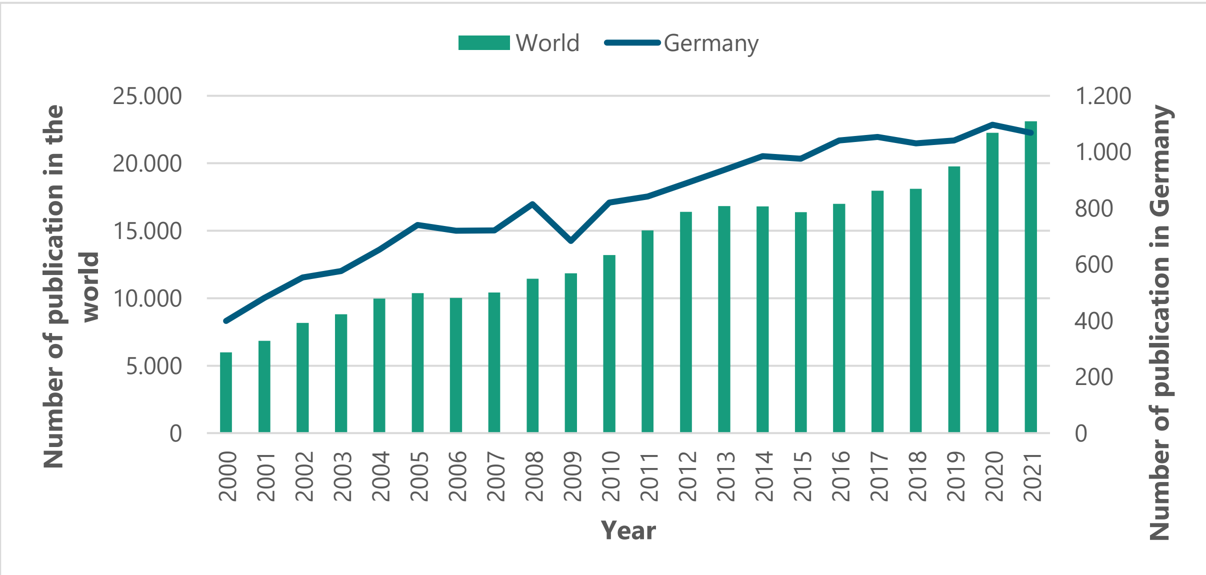
Second, advancements in biotechnology enables new solutions for feedstock provision, industrial bioprocessing, and several product groups and applications. Among others, modern techniques enable the exploitation of novel feedstocks (e.g. wood, algae, CO_2) and using side and waste streams, improvement of crops and maintaining and increasing soil fertility and agricultural productivity, with the potential of lower environmental impact and not further increasing pesticide and fertilizer inputs. Moreover, advancement in resource- and energy efficient bioprocesses or even carbon-neutral bioprocesses, side stream cascading, waste recycling (e.g. by plastic degrading enzymes) provide solutions to enable the transition to a carbon-neutral and circular economy. Finally, unique products not possible by other technologies or ones with new functionalities emerge, such as biopharmaceuticals, health-promoting food and feed ingredients, alternative proteins or cultured meat, novel antimicrobial agents, etc.

However, it is still a long way for biotechnological products and processes to enter the market and to be adopted by industry to a significant extent. A dominant perception is that industrial deployment of biotechnology has to speed up in order to harness the potential of bioeconomy. This means that a significant number of products, processes and services are "stuck" at medium technology readiness levels, but need to be brought to pilot, demonstration and commercialisation stage quickly. Often, high R&D&I-, investment- and production costs are a hindrance, the regulatory framework is not suited for such emerging technological trends or frame conditions favor non-biotechnical approaches over biotechnical ones, social and environmental effects are ambiguous in a significant number of cases (e.g. bioplastics), and acceptance by consumers and society is low for certain applications (mainly those involving genetic engineering, genome editing in agriculture and food production).

12.2 Publications and Patents

The publication analysis for biotechnology indicates a rise of publications over time with some stagnation in 2006 and 2015 (Figure 32). There is a relatively higher increase in 2020. Biotechnology publications in Germany have mainly increased until 2008, whereas they significantly decreased 2009. Afterwards they increased slightly until 2016 and are mostly stagnating since then. Aligning to this development Germany's share of world-wide publications over time slightly decreased from 7% in 2000 to 5% in 2021.

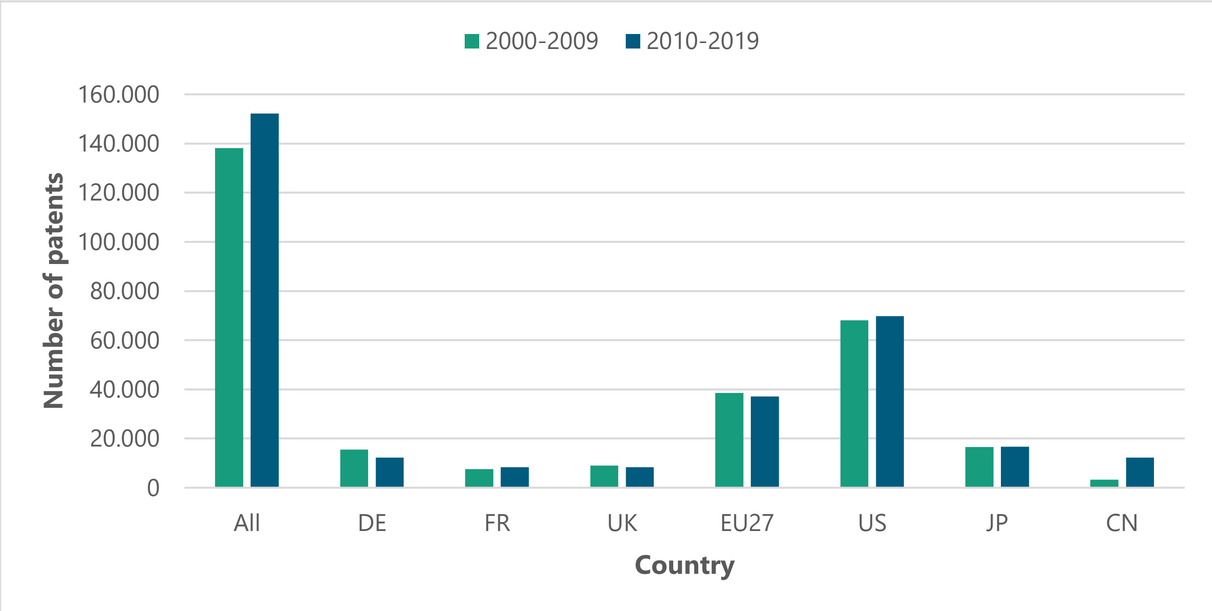
Figure 32: Publications for biotechnology 2000-2021



Source: Fraunhofer ISI based on Scopus

Regarding patents, the overall development is rather stable with a slightly higher number of patents in 2010-2019 compared to 2000-2009 (Figure 33). Patents in China increased the highest in recent years. While the USA are ahead of the EU-27, the development of both regions is similar as the numbers barely vary between both analysed time periods. The same applies for Japan and relatively also for France and the UK. In the analysed time periods, Germany is leading in the EU-27 with an average share of 36,5%. Nevertheless, this share is slightly decreasing.

Figure 33: Transnational patents in biotechnology, comparison of 2000-2009 and 2010-2019



Source: Fraunhofer ISI based on STN

12.3 Market Outlook

Biotechnology processes, products, and services and process are used in many different applications. This bears a challenge for measuring market size as well as impacts.

Commercial market studies estimate the market size to around 800 1100 bn US$ in 2021 and estimate a yearly growth of 13-15%, which would result in 3.400-3800 bn US-$ in 2030.[44] The health application segment holds the largest share and will continue to do so with around 50% of the market, while the rest is shared across food, agriculture, industrial processing, environmental applications etc.

Besides these few numbers from commercial market studies the information base– and similar for impact, see section below – is limited. From a political and partly stakeholder interest point of view, a pure technological perspective has been replaced by a more broader mission-oriented perspective. Hence, the attention on biotechnology and the publicly funded collection of data regarding adoption and impact has been reduced in the past decade. In particular, there are less attempts to collect internationally comparable firm data, e.g. as had been done by biotechnologie.de based on the cited OECD definition until 2020.[45]

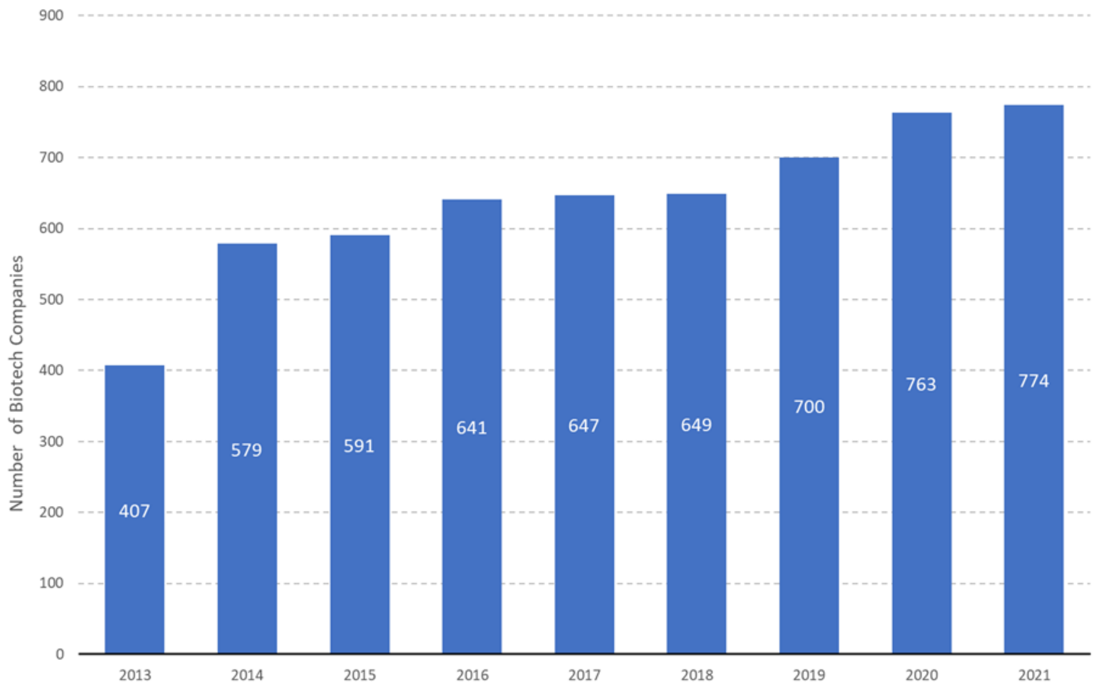
Still some reports especially cover the activities of dedicated small biotechnology firms. However, they do not or only partly cover activities of those companies for which biotechnological activities only present a certain share of overall company activities (e.g. BASF etc.).[46] The numbers of companies and in particular the number of employees grew steadily between 2014-2021.

[44] https://www.grandviewresearch.com/industry-analysis/biotechnology-market; https://www.biospace.com/article/biotechnology-market-size-to-worth-around-us-3-44-trillion-by-2030/

[45] https://biotechnologie.de/

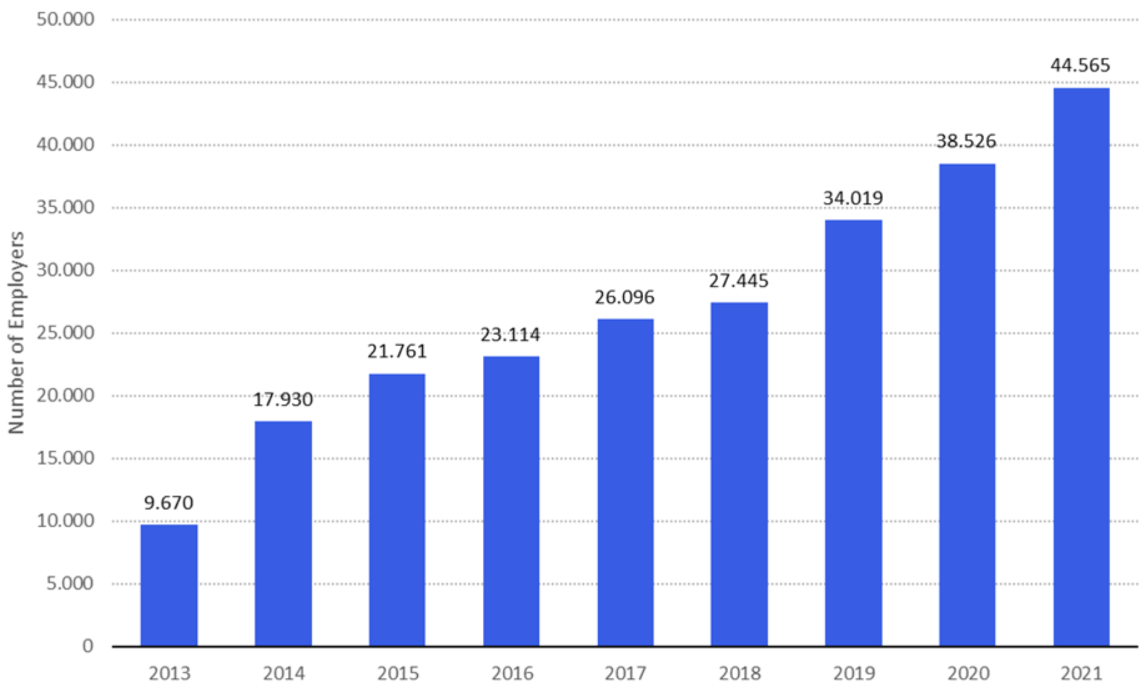
[46] This is most likely the reason why the presented numbers for biotechnology are partly lower than those for biopharmaceuticals alone, as it can be assumed that the latter partly include employees of larger firms as well.

Figure 34: Biotechnology Firms in Germany 2014-2021



Source: Klicken oder tippen Sie hier, um Text einzugeben.EY, BioDeutschland

Figure 35: Employees in Biotechnology Firms in Germany 2014-2021



Source: Klicken oder tippen Sie hier, um Text einzugeben.EY, BioDeutschland

Because of the limited data availability comparison between countries has become very difficult. According to a Benchmark report Germany performs well for capacities and innovation drivers due to an established industry and strengths in science and technology systems. A long-stated weakness is the access to private funds (Beall und Friedman 2020). After a significant increase of equity in the COVID-19 crisis with especially high funding-round for BioNtech the level fell back to 2019.[47]

12.4 Potential Impact

Biotechnology has had a significant impact on the global economy. It has already impacted several industries significantly, including healthcare, agriculture, and manufacturing, and has created new products, services, and markets (Chui et al. 2020). However, due to its broadness, the impact of biotechnology is hard to quantify.

Economic Impact

As an important economic channel, the biotechnology industry presents a limited but very productive sector. While the total numbers of firms and direct employment in Germany have been presented above, Haaf et al. (2020) aim to attribute value added and employment to the three fields health biotechnology, industrial biotechnology and agricultural biotechnology in the EU. Unsurprisingly, health biotechnology is by far the most important and contributes around 30 bn € direct value added in 2018 in the EU28, while industrial and agricultural biotech together contribute less than 5 bn €, so together 34.6 bn €. indirect and induced effects are estimated at additional 44.3 bn €.The EU biotechnology industry directly creates a total of 223,000 jobs in the healthcare, industrial and agricultural biotechnology sector. Moreover, it supports 710,500 jobs in the overall economy through indirect and induced effects. The average labour productivity of 154,500 € gross value added (GVA) per employee indicates that the biotechnology industry is a highly efficient and capital-intensive industry (Haaf et al. 2020).

In addition, biotechnology products and processes may have significant effects via process innovations, such as reducing costs and enabling new kinds of products and services in downstream industries.

Environmental Impact

In principle, biotechnology, due to inherent properties of organisms and enzymes used as production platforms, can support the substitution of fossil resources by renewable ones, save energy, significantly reduce CO2 emissions and lead to using and emitting less toxic substances. However, it is also linked to renewable resource depletion, water withdrawals and consumption, biodiversity loss, emission of greenhouse gases (incl. energy uses), and natural land transformation/occupation. The actual impact depends to a large extent on the concrete implementation of the process. Due to this ambivalence, a general discussion of the sustainability of the bioeconomy arises.

For those biotechnology processes that use biomass as feedstocks of course the land-related impacts are of crucial relevance. There are, however, industrial activities supported by biological processes (e.g. by the use of the enzymes) without significant land use. For the latter there are a set of often cited examples, where the substitution of the chemical process by a biotechnical one resulted in reduced energy consumption and related CO_2 emissions (e.g. for certain vitamins, detergents, paper or antibiotic production) (Venkatesh et al. 2019), but information on a broader level rarely exists.

Social impacts

[47] https://www.biodeutschland.org/de/pressemitteilungen/biotechnologie-industrie-sieht-pessimistisch-auf-das-neue-jahr.html?year=2023

Highly disputed is the societal and social impact of biotechnology. While proponents claim the high potential of biotechnology for the environment, human health and the economy in rural areas, concerns are raised regarding e.g. naturalness, risk issues, economic justice and partly sustainability.

12.5 Summary of relevance and suitability for case study selection

Biotechnology has high potential for efficiency in agriculture, for substituting chemical processes and fossil-based resources, for recycling and use of waste as feedstock and for delivering new products with superior performance and new services. However, the potential impact is also disputed and public acceptance is very low for certain applications (e.g. genetically engineering in agriculture and food production).

In principle, different biotechnology segments are promising. However, they are partly already covered in more detail in other technology field assessments in this study. Moreover, the further disaggregation does hardly increase the information basis for further assessment, some data are even only available for biotechnology as such, but not for sub-fields. Instead, a potential case study could more concentrate on enabling factor for future innovation and diffusion of biotechnology (e.g. skilled personnel, acceptance). However, this would hardly provide additional insights about the impact of biotechnology and the bioeconomy.

13 Technology Field Microbiome

13.1 Characterization of technology field

13.1.1 Definition and Delineation

A microbiome[48] is a microbial community — comprising e.g. bacteria, archaea, viruses, unicellular eukaryotes and fungi — and its functions that are characteristic of a specific habitat (e.g. soil, water, humans, plants or animals as hosts, being inhabited by microbiomes (Berg et al. 2020; D'Hondt et al. 2021). Microbiome functions are essential for natural and cultivated ecosystems and ecosystem services (Meisner et al. 2022). Only in recent years has it become possible to study microbiomes, thanks to scientific-technological progress. Scientifically, this means a paradigm shift in microbiology and microbial ecology research: Instead of studying only one or few selected microbial strains, composition, dynamics and functions of complex microbial communities (microbiomes) can now be analysed qualitatively and quantitatively. Techno-economically, this provides the knowledge base for targeted manipulation of microbiomes or engineering of microbial communities with tailored functions (European Commission et al. 2021).

13.1.2 Current status and potential future developments

Microbiome research is a field that is driven by highly sophisticated technology development. Key enabling technologies are so-called multi-omics technologies (Berg et al. 2020). The comprise high throughput isolation (high throughput culturomics) and visualization (microscopy), single cell genomics, metabarcoding and metagenomics for probing the taxonomic composition and the metabolic potential of microbiomes, and metatranscriptomics, metaproteomics and metabolomics to analyze microbial activity. Imaging and reporter systems are applied to assess and quantify functions and 3D organization of microbial communities. Last but not least, these approaches deliver an enormous quantity of complex data which can only be analysed and interpreted with the help of sophisticated bioinformatics, and artificial intelligence methods. This still developing toolbox allows the analysis of the microbial potential in a given environment ("who is there?"), of the metabolic potential ("what can they do?"), and of the microbial function ("what are they doing?") (Berg et al. 2020).

Microbiome research has developed dynamically since the start of the Human Microbiome Project[49], funded by the U.S. National Institute of Health, in 2007/2008. Microbiome research is now firmly established in many scientific disciplines well beyond human medicine, especially in agriculture (crop and livestock production, plant protection, veterinary medicine, soil health), food science, biotechnology, bioeconomy, environmental sciences, as well as informatics and artificial intelligence.

[48] The term "microbiome" is often used interchangeably with the term "microbiota". However, microbiota refers to the actual organisms ("bugs") within a microbial community, whereas microbiome means the organisms of a microbial community in functional interaction with their environment (STOA 2021; Berg et al. 2020).

[49] https://www.hmpdacc.org/hmp/overview/

Major research areas (in terms of publications and projects) are human microbiomes, especially gut microbiomes, followed by microbiomes in agricultural primary production systems (plants and livestock farming), in the environment (mostly soils), microbiomes in waste streams, and microbiomes in food products and processing (Meisner et al. 2022).

Microbiome research has already resulted in important insights. Some examples are listed below (Berg et al. 2020; D'Hondt et al. 2021; Meisner et al. 2022; STOA 2021):

Microbiomes are essential for maintaining life on Earth, e.g. in producing oxygen, in carbon sequestration, in nutrient recycling, in nitrogen and methan fixation, thus contributing to fertilization and GHG mitigation effects.

All animals, plants and humans are meta-organisms which incorporate microbiomes as "a second organism". These microbiomes play crucial roles in health and disease.

Composition and functions of microbiomes are dynamic. Diversity loss within microbiomes or loss of microbiomes from environments (e.g. from soil due to agricultural practices) can result in so-called "dysbiosis". This is understood as a change of the microbiome composition, resulting in altered functions, and can severely impact health and ecosystems services.

Microbiomes are functionally connected and interact with one another. Dysbiosis in the microbiome in one ecosystem may influence microbiome functions in another ecosystem linked to it.

Different types of microbiome research can be distinguished (Meisner et al. 2022):

Observational and descriptive studies: The focus is on the description of the composition of the microbiota in a given environment. More recent developments go beyond bacteria and study a broader range of organisms in the microbiome, analyse the spatial distribution and changes over time or in response to altered environmental factors (e.g. changes in soil microbiome composition in drought, compared to wet soil), and distinguish in these changes between transient and resident fractions of the microbiome.

Studies exploring functions and mechanisms. Microbiome functions (e.g. metabolic pathways) are studied, also under changing conditions, and the impact on ecosystem functioning is investigated, thus looking into cause-effect relationships. Of high interest is the elucidation of resistance and resilience against disturbance of the ecosystem, because knowledge of the underlying mechanisms is essential for the development of targeted interventions to improve microbiome functions.

Microbiome modulation to improve ecosystems functions. Microbiome alterations could in principle be achieved by

directly introducing "healthy, beneficial" microbiomes (this approach is e.g. followed in stool transplantation to treat diseases of the gut),

applying a limited number of defined (and perhaps genetically engineered) microorganisms with the desired properties and functions,

applying metabolites which have a desired effect either on the microbiota or the host,

changing environmental conditions so that microbiomes respond by shifting their composition and activity from dysbiosis to a healthy state (e.g. changing dietary habits to im prove gut microbiome functions; changing agricultural practices to improve soil microbiome functions)

All these microbiome modulation approaches are intensively studied e.g. in personalized medicine: It is under investigation whether microbiomes could be shifted from dysbiosis to a "healthy state" by therapeutics, dietary changes, and/or the administration of pre- or probiotics, synthetic microbiota or microbiome transplants.

The focus of microbiome research is still on descriptive approaches and trial-and error approaches in attempts to modulate microbiome functions towards the desired state. Therefore, more targeted, tailored, knowledge-based approaches require a better understanding of the underlying mechanisms and cause-effect-relationships. Moreover, microbiome studies most often investigate microbiomes within one ecosystem. Therefore, the connections with other ecosystems and the interaction of microbiomes of linked ecosystems is not yet well understood (Meisner et al. 2022).

Large potentials are assigned to microbiome applications to provide solutions to global challenges (D'Hondt et al. 2021; European Commission et al. 2021; FAO 2022a; FAO 2022b; Trivedi et al. 2021; Michl et al. 2023) in the above mentioned areas of

- human, animal and plant health,
- maintaining agricultural productivity by complementing or even replacing chemical fertilizers and pesticides and by conferring resistance or tolerance to diseases and harmful environmental conditions (e.g. drought, extreme temperatures),
- treatment of waste streams in a circular economy,
- food production and prevention of food spoilage,
- climate change adaptation and mitigation.

Table 15: Drivers and barriers for microbiome research and applications

Drivers	Barriers
Scientific-technological advances enable to analyse composition, dynamics and functions of microbiomes qualitatively and quantitatively, continuous development of new techniques and equipment	Lack of consensus on best practices in microbiome research, lack of standards, need for data standardization
Large potentials are assigned to microbiome applications to provide solutions to global challenges	Microbiomes are still not addressed explicitly in many R&D&I strategies
Large potentials for new products, services and practices	Need for a more rapid transfer of knowledge from basic science into practice
Microbiome R&D is an integral part of many research and application fields, including human health, agriculture, livestock farming, environmental protection and climate change mitigation and adaptation, food and nutrition.	Microbiome research is strongly driven by methods; should be driven more by hypotheses and concepts. Is still too descriptive, lack of understanding of underlying mechanisms of microbiome and ecosystems functions
Common concepts, research questions and methods in different research and application fields, as prerequisite for knowledge exchange, knowledge transfer and collaboration between the fields	Need for better coordination and collaboration, between research projects, between scientific disciplines, transdisciplinary between key players along value chains, internationally
Large pharmaceutical, agricultural and food companies as well as dedicated, highly specialised SMEs pursue microbiome applications	Regulatory issues: many microbiome products would fall into a new regulatory class. Need to develop and implement regulatory frameworks for microbiome applications in health, agriculture, food, waste and environment

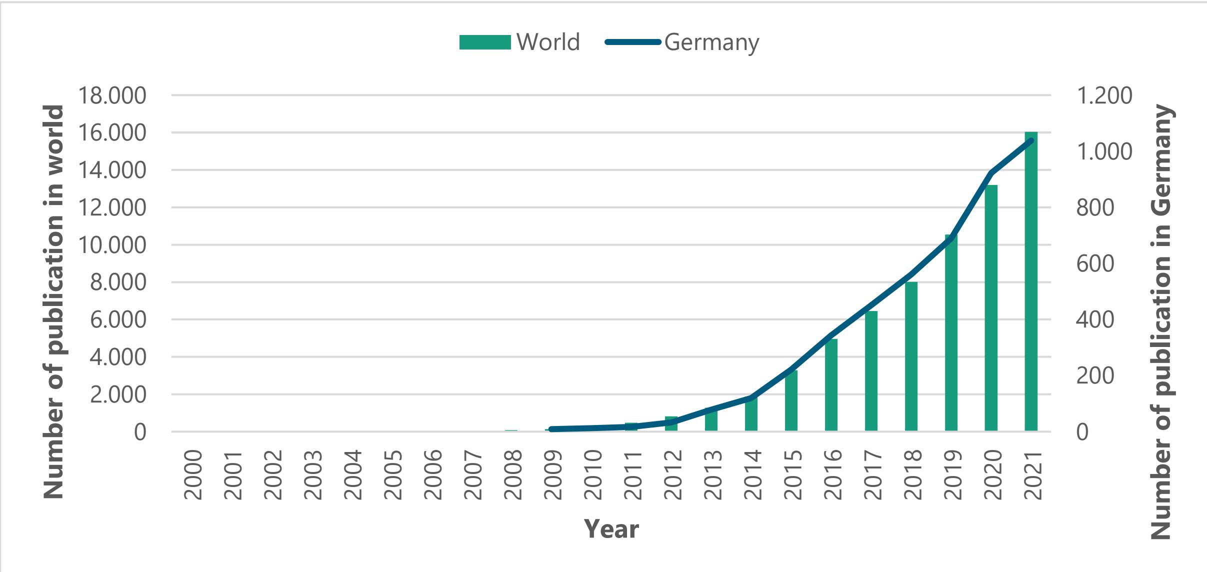
	Technological challenges, e.g. establishing long-lasting modifications of microbiomes for desired functions
	Manufacturing microbiome therapeutics at scale is more difficult than for chemical manufacturing

Source: Wydra et al. (2018); Berg et al. (2020); D'Hondt et al. (2021); Donnell und Paterson (2021); Meisner et al. (2022); Waltz (2023)

13.2 Publications and Patents

The publication analysis for microbiomes shows, that there were occasionally publications in the early 2000s, however, since 2009 the numbers started to grow faster (Figure 36). Since then publications increased rapidly until 2021. The development in Germany was relatively aligned to the described one. Nevertheless, the first two publications in Germany happened in 2007, which indicates that the early research was in other countries. Therefore, Germany's share of world wide publications over time was 0% until 2007 and afterwards continuously between 6-7% except 2011 and 2012 with 4%.

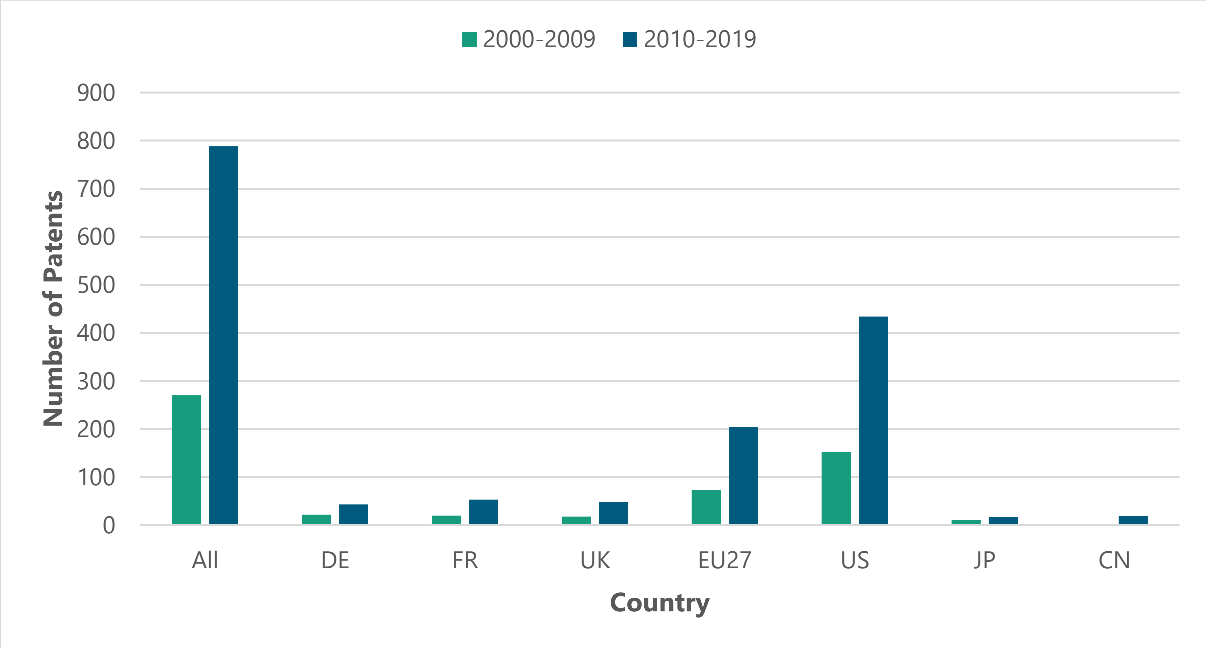
Figure 36: Publications for microbiomes 2000-2021



Source: Fraunhofer ISI based on Scopus

Patents in microbiomes almost tripled in 2010-2019 compared to 2000-2009 (Figure 37). The two biggest regions over the time are the EU-27 and the US, however, the US has as double as many patents as the EU-27. Both had a similar rise of patents between the two time periods as the decribed world-wide growth. Germany's share of patents in the EU varies highly over the time and is lower than in France and UK. Other included countries also increased their numbers fast in the second period.

Figure 37: Transnational patents for microbiomes, comparison of 2000-2009 and 2010-2019



Source: Fraunhofer ISI based on STN

13.3 Market Outlook

While the focus of activities regarding microbiomes is still on R&D in order to build the required knowledge base, various industrial players (e.g. dedicated biotechnology companies, technology service providers, pharma and multinational food companies, food ingredient producers, consumer goods companies, medical device companies, agro-chemical companies, feed companies) engage in the field with the aim to commercialise services and products.

While some products and services have entered the market, most products are still in R&D phase and it depends on various market drivers and barriers, whether there will a broad diffusion in the forthcoming years.

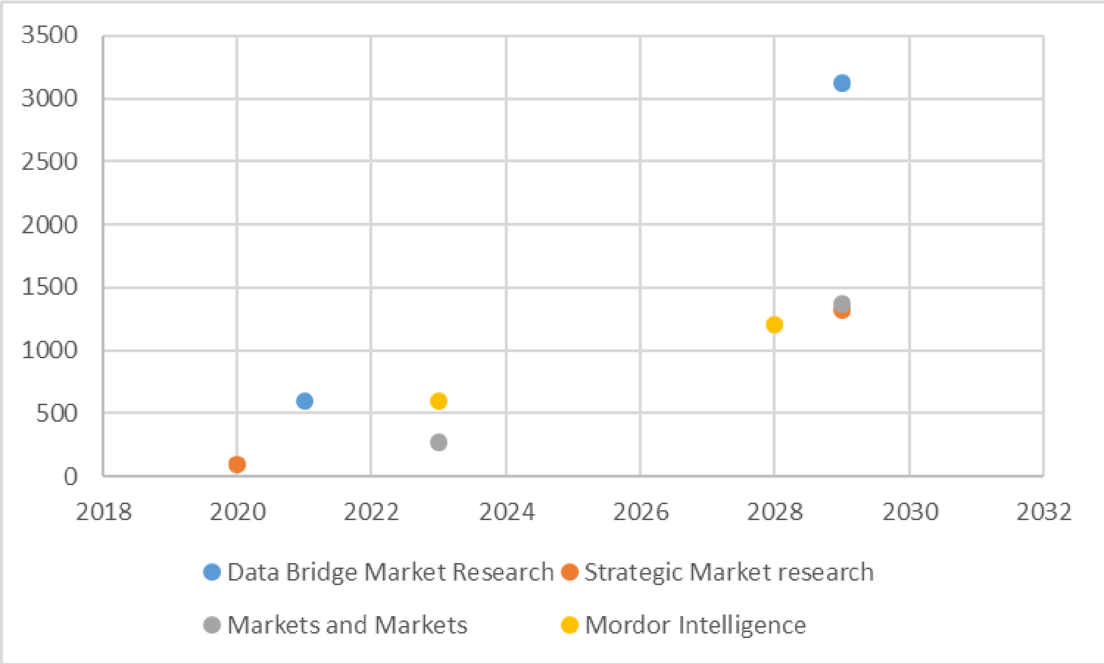
Market estimations and outlooks for microbiome differ widely as the example of few selected market outlooks for the Human Microbiome market globally shows (Figure 38). As a common point all outlooks expect that the market grows considerably and will exceed 1 bn US-$ at the end of the decade.

Very recently, two microbiome-based therapeutics have received market approval by the Food and Drug Administration (FDA) in the USA:

In November 2022, the U.S. Food and Drug Administration approved the first fecal microbiota product: Rebyota from Ferring Pharmaceuticals Inc. Rebyota is prepared from stool donated by qualified individuals and thus represents a form of fecal transplantation. Rebyota is approved for the prevention of recurrence of Clostridioides difficile infection (CDI) in adults after completed antibiotic treatment for recurrent CDI. The application was granted Fast Track, Breakthrough Therapy and Orphan designations (Mullard 2022; Food and Drug Administration 2022).

In April 2023, the U.S. Food and Drug Administration approved the first fecal microbiota product that is taken orally: Vowst from Seres Therapeutics Inc. The multinational food company Nestle is also involved. Vowst is approved for same condition as Rebyota. The application was granted Priority Review, Breakthrough Therapy and Orphan designations (Food and Drug Administration 2023).

Figure 38: Market Outlook for Human Microbiome



Source: Data Bridge Market Research[50], Strategic Market Research[51], Markets and Markets[52], Mordor Intelligence[53]

Fewer market studies are available for soil microbiome. Fortune business insights estimates that the agricultural microbials market will see a CAGR growth of 14.27%, with market size increasing from USD 4.64 billion in 2020 to USD 11.81 billion in 2027.[54] Large agricultural companies pursue own R&D activities, or collaborate closely with specialized SMEs. The large agricultural companies presently pursue different strategies whether applications are developed inhouse, through acquisitions or by collaborations with specialized SMEs. Several SMEs market microbial solutions by themselves, without the need to partner with big ag companies (Waltz 2023).

There is hardly any specific information available for Germany in terms of activities and market. As shown in section 13.2, Germany is competitive in science and technology and in principle has a large potential market for microbiome. Available information from private market research indicates that Germany dominates the market in terms of market share and market revenue and will continue to flourish during the forecast period, mainly because of its relevance as market for health.

13.4 Potential Impact

The microbiome is important for many aspects of human health as well as preserving ecosystem, supporting agricultural production and circular economy.

Economic and Social Impacts

Microbiomes have the potential of enabling novel products, treatments and interventions/practices with new functionalities/modes of action in a range of sectors, especially prevention and treatment of diseases both in human and veterinary medicine, innovations in the pharmaceutical industry

50 https://www.databridgemarketresearch.com/reports/global-human-microbiome-market

51 https://www.strategicmarketresearch.com/market-report/human-microbiome-market

52 https://www.marketsandmarkets.com/Market-Reports/human-microbiome-market-37621904.html

53 https://www.mordorintelligence.com/industry-reports/human-microbiome-market

54 https://www.biocompounding.com/a-deep-dive-into-the-microbiome-market-landscape/

(microbiomes as therapeutics or as targets of medicines), food/feed, agricultural production (Meisner et al. 2022). The industrial scene consist of a limited set of firms, with some specialized SMEs and some large food/pharma companies explicitly active in microbiome research. The direct impact of these firms in terms of value added and employment is either limited or, in the case of large firms in which microbiomes are only part of the company portfolio, difficult to calculate or estimate.

However, microbiome-based products and services may result in significant indirect economic effects. "Unhealthy" microbiomes are associated with a broad spectrum of different diseases (e.g. infection, autoimmune diseases, cancer, metabolic diseases, and neurological diseases), affecting large numbers of the population. If interventions were available which could revert "unhealthy" microbiomes to normal ones and thus contribute to improve the patients' health status, this might result in reduced health care costs, a healthier population and a potentially more productive labour workforce (Banerjee und van der Heijden 2022; Donnell und Paterson 2021; STOA 2021). In the same vein, more efficient agricultural livestock and plant production and reduced ecosystem burden could avoid rising costs in agricultural production (FAO 2022a).

Ecologic Impact

Microbiomes can enhance the use of organic and waste streams, enhance bioremediation and degradation of toxic contaminants, reduce landfill content, thus help to support recycling and to establish a circular bioeconomy. Moreover, they can be used in the prevention of food spoilage, thus reducing food waste.

In agriculture, microbiome-based solutions can provide alternatives to chemical pesticides and fertilizers with fewer damaging effects to the ecosystem while maintaining productivity, support plant resilience or tolerance against pests and adverse environmental conditions as well as enhance carbon sequestration ability by supporting soil health and via changing farming practices (FAO 2022a, 2022b). E.g. progress is reached in the application of plant microbiomes for increasing crop yields and improving salt and drought tolerance of crops. Soil microbiomes can be applied as bio-fertilizers for soils and can reduce nitrogen leaching (Michl et al. 2023). The World Economic Forum estimates microbiome technologies could increase primary production by up to 250 million tons while simultaneously reducing GHG emissions by up to 30 megatons of CO_2 equivalents, mainly through reducing the use of inorganic fertilizers (D'Hondt et al. 2021).

Applications of microbiomes in livestock production aim at increasing the digestability and nutrient availability of feed so that feed is more efficiently used. Moreover, microbiomes in the gut of ruminants are being modified in a way that methane emissions will be reduced, in this way contributing to climate change mitigation measures.

But most of these applications are still in R&D&I phases and long-term effects/unintended side effects still need to be investigated (D'Hondt et al. 2021).

13.5 Summary of relevance and suitability for case study selection

The ability to analyse and also engineer microbiomes is an emerging key enabling technology in the bioeconomy. It significantly expands the extent to which humans can engineer and tailor different processes in nature for human purposes (e.g. health/disease, nutrition/digestion, soil fertility, ecosystem services). There is significant potential for wide use of microbiome engineering and wide impact for health and environment. Still, many developments are still in the R&D phase and have not yet entered the market. It has still to be seen whether different market barriers (e.g. consumer acceptance, regulatory approval, claims for benefits) can be overcome.

For a potential case study, the broad spectrum of application fields is challenging. Hence, further focus would be needed. Potentially an in-depth assessment e.g. for soil microbiome may synthesize insights about the innovation patterns and system (e.g. with more in –depth bibliometric indicators) and estimations of ecological impact.

14 Technology Field Carbon Capture and Use (CCU)

14.1 Characterization of technology field

14.1.1 Definition and Delineation

Carbon Capture and Use (CCU) is the use of captured carbon, in most cases as CO_2, as a raw material, and to convert this feedstock into value-added products in organic synthesis, e.g. polymers, minerals, chemicals, and synthetic fuels (European Commission et al. 2019; Purr und Garvens 2021).

CCU can be understood as a carbon recycling technology. It broadens the spectrum of options for recycling of carbon-based chemicals or materials, both from fossil and biogenic sources. It may contribute to establishing a circular (bio)economy. It bears the potential to provide an additional, up to now barely used feedstock to organic (bio)synthesis, thus reducing the need for using "fresh" fossil resources or biomass for industrial production processes.

If carbon can be efficiently recycled by CCU, it will contribute to close - together with other recycling approaches and at least to a certain extent - industrial carbon cycles. (Only) under certain conditions (see below), it can contribute to reduce the use of fossil feedstocks and to reduce CO_2 emissions.

The direct utilisation of CO_2, without conversion, (e.g. as solvent, in the drink industry, as fertilizer in greenhouses) is out of the scope of this technology field.

CCU also differs from the end-of-pipe technology of Carbon Capture and Storage (CCS) which aim at storing CO_2 underground permanently. CCS is not addressed in this technology field.

Photosynthetic organisms (e.g. crop plants, trees, photosynthetic bacteria, cyanobacteria, algae) are capable of capturing CO_2 and convert it into biomass and value-added products, using the energy of sunlight. They are not in the focus of this technology field. However, the potential of autotrophic organisms (i.e. using CO_2 as carbon source) in CCU approaches will be covered.

14.1.2 Current status and potential future developments

CCU comprises a broad spectrum of different CO_2 sources, different technologies, reaction routes, product groups and their uses, in a large number of possible combinations.

As a first step, CO_2 has to be captured. The higher the concentration of CO_2 and its purity, the less costly and technologically demanding is the required technology for capturing CO_2. The most advanced and widely adopted capture technologies are chemical absorption and physical separation. Potential CO_2 point sources are industrial processes for manufacturing ammonia and H2 from natural gas, iron, steel and cement production, fermentation processes, biogas plants, power plants and waste incineration. It is, however, the goal of energy policies to reduce the use of fossil energy as much as possible, and replace it by renewable energy. In the long term, CCU should therefore be only used for technologically inevitable CO_2 emissions, e.g. in cement or steel production. Moreover, CO_2 can be captured directly from ambient air, in so-called Direct air capture (DAC) processes. They are at pilot/demonstration level.

CO_2 is a stable molecule which does not readily react. It can only be converted by providing energy, either directly or in the form of reaction partners, and/or with the help of appropriate catalysts. Progress in catalysis research and development is therefore crucial for the further development of CCU technologies. Six different categories of CO_2 conversion can be distinguished and are listed below (European Commission et al. 2019, p. 35). Biotechnical processes for CO_2 conversion are also under development (Hüsing et al. 2021); examples are given in the respective categories:

Chemical – non-hydrogenative: Chemical conversion of CO_2 without hydrogen as a co-reactant. The CO_2 molecule is incorporated into the product (e.g. polycarbonate, polyols for polyurethan foam production (Covestro)).

Chemical – hydrogenative: Chemical conversion of CO_2 with hydrogen as a co-reactant and reduction of the carbon atom (e.g. methane, methanol, ethylene, propylene). This category overlaps with power-to-X approaches. Hydrogen is produced by water electrolysis, powered by renewable electricity (wind, photovoltaics), and reacts with CO_2. Autotrophic bacteria are also capable of synthetising organic molecules from CO_2 and H_2. They can produce more complex molecules with higher functionalisation than power-to-X (Hüsing et al. 2021).

Biological CO_2 conversion by photosynthesis (plants, algae, cyanobacteria), e.g. to carbohydrates, proteins, fats and oils, fine and speciality chemicals.

Electrochemical Reduction of the CO_2 carbon atom by adding electrons: the electron source can either be an applied current or a semiconductor exposed to light (photocatalysis). In bioelectrosynthesis, microorganisms are provided electrons by an applied current in order to convert CO_2 into organic molecules (Bakonyi et al. 2023)

Photochemical Reduction of the CO2 carbon atom by solar energy (artificial photosynthesis).

Inorganic Fixation of CO_2 in inorganic compounds (carbonates, e.g. Ca- and Mg-carbonates or soda ash).

According to European Commission et al. (2019), the most represented routes are chemical non-hydrogenative and chemical hydrogenative. Products obtained through these two routes have either a relatively low technology readiness level (TRL 1–3) or a high one (TRL 7–9). Products from biological, electrochemical or photochemical conversion are generally at a low maturity level (TRL 1–3). TRLs of products derived from inorganic synthesis are distributed equally over all maturity levels (European Commission et al. 2019, p. 41).

CCU products can be classified into three usage groups: chemical products, energy products (e.g. methane, synthetic fuels) and materials (e.g. plastics, building materials).

In addition to - partly - low technological maturity, economic considerations are important for future development of CCU technologies. Key factors to be taken into account are the (point) sources of CO_2, its concentration and purity and the availability and pricing of renewable energy, the proximity between CO_2 sources and CO_2 use industries, together with the availability of CO_2 transport infrastructure. According to IEA, there is a need to demonstrate novel CO_2 capture routes (e.g. direct air capture, membranes) and to increase the energy efficiency of CO_2 conversion processes, naming CO_2 electrolysis and plasmosis, and solar-based thermochemical conversion as options. In building materials, IEA sees a need for long-term trials of CO_2-cured concrete to demonstrate its reliable performance in structural applications[55].

For the implementation of large-scale CCU operations, much lower renewable electricity costs, lower investment costs for water electrolysis for hydrogen production and continuous processes (which would require storage of hydrogen or renewable electricity) are required (acatech 2018).

There are intensive discussions ongoing whether or under which conditions CCU can contribute to achieving climate policy goals and can be considered an instrument for mitigating climate change. CCU does not necessarily reduce GHG emissions. If the recycled CO_2 is derived from fossil resources, it will result in additional net emissions of CO_2 into the atmosphere, at the end of the product use cycle: this means that the CO_2 emissions into the atmosphere were only shifted in time and place, but were not reduced. Moreover, the CO_2 recycling process itself is energy-intensive. Purr und

[55] https://www.iea.org/reports/co2-capture-and-utilisation

Garvens (2021) estimate that about double the amount of electrical energy is needed for a CCU product, compared to the fossil product it replaces. For climate protection, CCU should only be a large-scale option if the share of renewable energies in the German energy system is above 80 %, and CO_2 should be mainly sourced from the atmosphere or from sources where CO_2 emissions cannot be avoided technologically (Purr und Garvens 2021). Nevertheless, given the long R&D&I periods needed to achieve industrial scale, CCU options need to be intensively developed now. Early demonstrations can contribute to refining and reducing the cost of CCU and support the future deployment[56].

Table 16: Drivers and barriers for CCU

Drivers	Barriers
Ambitious industry decarbonisation targets in Germany and the EU	Technological challenges, many technologies still at low TRL, need to reduce energy demand and improve process efficiency and yield CO_2-based production capacity is likely to remain marginal until 2030
CO_2 as cheap and abundant feedstock for decarbonization of industries	Economically not viable under present frame conditions, need for substantial policy support
CCU makes it possible to generate value from CO_2	Large scale implementation depends on a high share of renewable energy in the German energy mix Using fossil power plants as CO_2 sources may delay the transition to renewable energy
CCU recognized as a means to close carbon cycles, to contribute to industrial innovation, to reduce the reliance on fossil resources and imports	High uncertainties regarding the technological and economic feasibility. Economic, commercial and technical data is highly technology- and case-specific and therefore project-specific. Data cannot be generalised for all products since economic and environmental data also depend on location, CO_2 input sources, type and cost of energy supply, infrastructure, proximity between CO_2 sources and user industries
Need for carbon as feedstock especially for the chemical industry, if energy supply is decarbonized	climate benefits (net carbon emission reduction) need to be thoroughly calculated for each specific application, may vary widely
Potential to reduce biomass use conflicts by providing an additional carbon source	Life cycle analysis of CCU applications can lead to very different results depending on the specific technologies considered; need for standards how to assess CCU

[56] https://www.iea.org/reports/co2-capture-and-utilisation

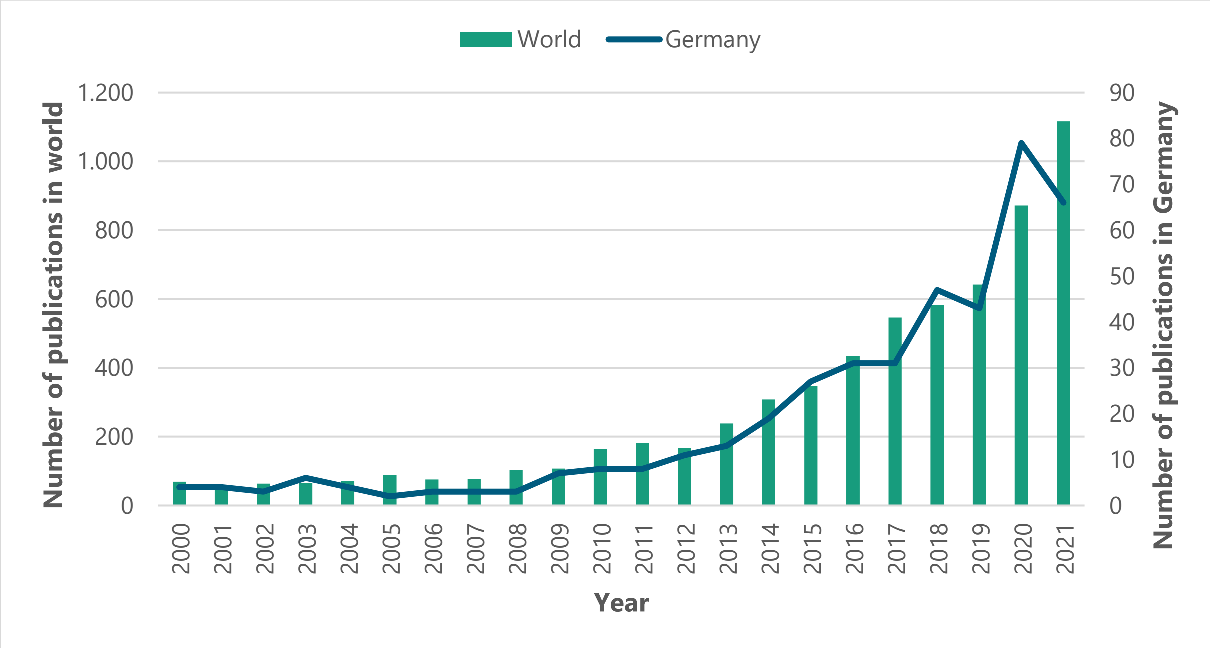
Circular (bio)economy as policy goal, CCU can contribute to establishing a circular (bio)economy	CCU technologies are unlikely to create completely novel products
Biotechnical processes broaden the scope of promising CCU technologies, especially for higher functionalised products, publicly funded Bio-CCU R&D projects ongoing	High investments needed for scale-up and first-of-a-kind plants
Need recognized to develop CCU technologies now in order to have them available at industrial scale when prerequisites have been established (e.g. high share of renewable energy (>80 %) in German energy mix, infrastructures, industrial symbiosis in cross-sectoral collaborations etc.	Lower scale of plants compared to fossil fuel use
CCU demonstration projects are eligible to bid for support in the EU ETS Innovation Fund under the EU Emissions Trading System (EU ETS)	Regulatory challenges, e.g. clarification needed to what extent greenhouse gas (GHG) emissions transferred to Carbon Capture and Utilisation (CCU) installations should be deductible
	Lack of a coherent policy and regulatory framework which gives proper incentives and avoids trade-offs of CCU technologies

Source: Dammer et al. (2019); European Commission et al. (2019); Bringezu et al. (2020); Hüsing et al. (2021); Purr und Garvens (2021) ; Zimmermann et al. (2020)

14.2 Publications and Patents

The publication analysis shows a steadily evolution until 2009. Since then the patents increased substantial, particularly, from 2019-2021 (Figure 39). The development in Germany was similar, but the growth started a little later in 2011 and with two interruptions in 2019 and 2021. Germany's share of world-wide publications varies widely and is 5,9% on average.

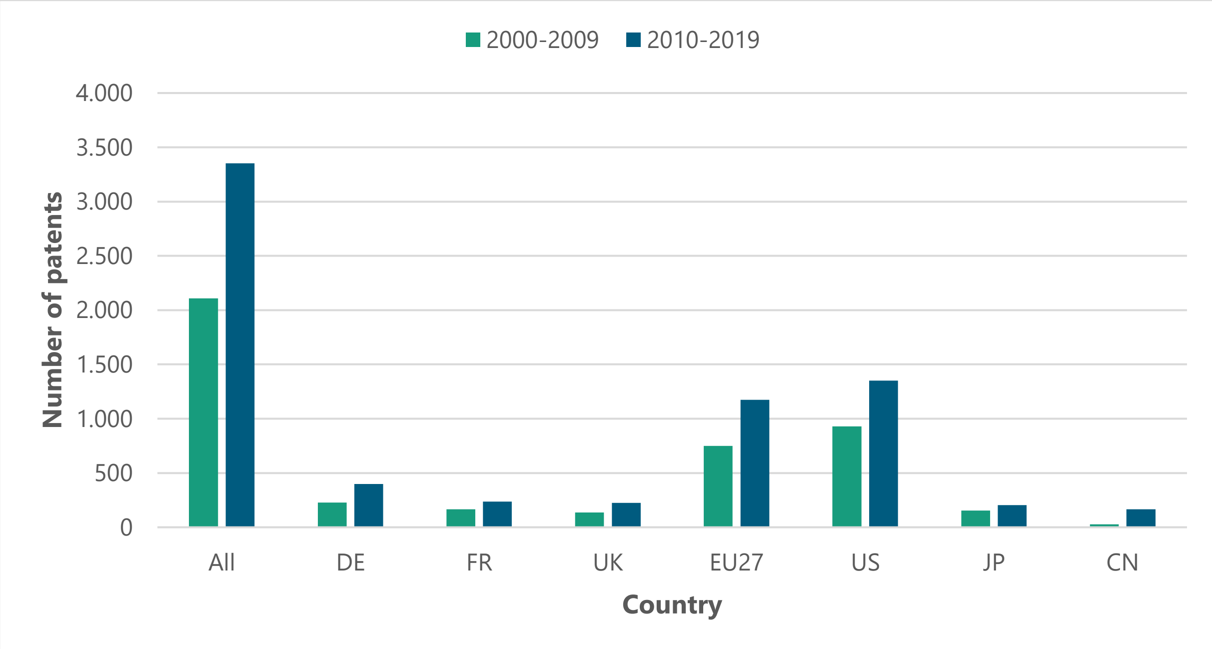
Figure 39: Publications for carbon capture and utilization 2000-2021



Source: Fraunhofer ISI based on Scopus

World-wide patents in carbon capture and utilization increased steeply when comparing the numbers from 2000-2009 and 2010-2019 (Figure 40). Nevertheless, it should be mentioned, that the numbers increased until the peak in 2011 and then relatively decreased until 2014. The US are slightly ahead of the EU-27. Both show a higher number in the last 10 years. The same trend applies for all included countries, whereas China recently had by far the highest growth rate, especially since 2015 (graphs not shown). Germany is generating 32% of the patents in the EU-27 on average over the time period.

Figure 40: Transnational patents for carbon capture and utilization, comparison of 2000-2009 and 2010-2019



Source: Fraunhofer ISI based on STN

14.3 Market Outlook

The commercial usage of CCU is still in an early stage and technological diffusion highly uncertain (see drivers and barriers). CCU-based processes require new production facilities or additional modules to existing plants. Therefore, the demonstration of such CCU processes and their scale-up to industrial size is likely to take several years of preparation. Hence, CCU-based production capacity is unlikely to rise very fast in the coming years. The speed will depend on technological development as well as whether frame conditions support or hinder investment in such industrial facilities. The medium and long term diffusion depends on large scale investments. Hence, existing analysis based on public announcements of operating plants expect increasing development activities, but only limited growth of production capacities in the coming years.[57]

But, as CCU may play a significant role in reaching climate neutrality in industry, a very significant increase of operations is discussed. A few scenario analysis have been performed to make what-if assessments of potential developments of CCU. In their scenario assessment for chemicals and polymers in Germany, Bringezu et al. (2020) distinguish between two scenarios, which differ among others in consumption and industry recycling rates, but especially regarding the utilization rate of large CO_2 point sources. They show a large corridor for the development of CCU for the chemical and plastics sector. This is calculated by the secondary input rate (SI-rate) that measures the percentage of secondary material within the total material input and – assuming that no other alternative is used – indicates the relevance of CCU for total carbon input use. The SI rates for the chemical sector would reach 5-27% in 2030 and 18-88% by 2050. The secondary input rates for the plastics sector vary between 22% - 45% in 2030 and between 43% - 100% in 2050 (Bringezu et al. 2020).

In Germany, no larger production facility is operating yet. But there are many research projects for the use of CO_2 at the laboratory level and close to pilot or demonstration plant (Cames et al. 2022).

[57] https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage

Overall, Germany has a large potential in carbon capture utilization market with its large chemical industry, which has a highly developed structure in terms of infrastructure, research and production facilities, and access to the national and market.[58] However, large-scale industrial production still remains to be reached (Cames et al. 2022).

14.4 Potential Impact

CCU technologies have the potential to foster transitional processes toward a circular economy. To date technology feasibility and economic viability are still main challenges and the assessments face high uncertainties regarding the future development of CCU technologies and its context.

Economic Impact

The economic viability is currently a major bottleneck. If significant price competitiveness can be achieved, CCU would be a possibility for domestic user industry to have sustainable resources without significant rise of resource exists, at least compared to alternative scenarios. Hence, the effect may be that existing industries in Germany may stay competitive in the future and still will contribute to value added and employment in the future. Any higher costs that will arise via CCU may lead to delocalization or lower consumption opportunities for other products (due to rising prices). However, Kaiser et al. (2022) assess among others the economic effects for polymer products, such as packaging, construction material or medical products. They conclude that the additional costs for CO_2-based value chains are rather small (< 5%) ,depending on scenario assumptions. This would imply that market entrance for CO_2-based polymer products could be possible due to only slightly higher prices, which might be realizable (Kaiser et al. 2022).

The distribution of economic effects will differ between the actors along the value chains (Kaiser et al. 2022; Naims 2020). Equipment manufacturers could receive higher revenues through massive investments in new plants and contribute directly to economic growth. Material and fuel producers act as "problem solvers" by offering competitive ways of utilizing CO_2. For high-emitting producers, higher production costs may arise that may only partially be compensated by higher revenues.

Environmental Impact

Concerning sustainability impacts, frameworks for comparative assessments, are just evolving. Among others, there are questions of system boundaries like the inclusion or exclusion of CCU upstream processes in the system as well as a common understanding of key indicators (Zimmermann et al. 2020). According to various existing assessments, CO_2 as feedstock does not automatically guarantee sustainable but provides significant potential for reduction of environmental impacts, notably global warming/climate change, compared to conventional manufacturing processes of the same product (Garcia-Garcia et al. 2021; Bringezu et al. 2020). But these positive environmental impacts can only be achieved if renewable energy is used (Bringezu et al. 2020; Garcia-Garcia et al. 2021). Moreover, the effects depend significantly on the product or service which the CO_2-based product replaces, on the carbon intensity of the energy used for the conversion process, and how long the CO_2 is retained in the product.[59]

[58] https://www.iea.org/reports/carbon-capture-utilisation-and-storage-2

[59] https://www.iea.org/reports/co2-capture-and-utilisation#

14.5 Summary of relevance and suitability for case study selection

If CCU becomes a central element for the decarbonization of various industries, the relevance would be enormous. Although the technologies used does not fit into certain definitions of the bioeconomy, as mostly no "biogenic resources" are used, CCU may have high implications for the bioeconomy. It may relieve to a certain extent biomass use conflicts, as it would provide an alternative feedstock for chemicals and materials. However, this could also mean that biotechnology-based solutions maybe partially displaced by chemistry and hence limiting the role and relevance of the bioeconomy. On the other hand, biotechnical CCU processes (Bio-CCU) (e.g. gas fermentations, electrobiosynthesis etc) might have a comparative advantage over chemical CCU technologies, especially for the synthesis of more complex, functionalized molecules.

A potential case study could look in more detail into different CCU scenarios to analyze and understand the impact especially in the context of the bioeconomy. Of special interest could be questions how demand for industrial use of biomass could be reduced if CO_2 could be used as an additional feedstock, to which extent biotechnical CCU processes gain a significant market share, and what the impact on biomanufacturing in the chemical and plastics industry might be.

15 Summary of Findings

15.1 Overall assessment of technology fields

The assessment of the 12 technology fields in the context of the bioeconomy provides valuable insights into the potential development and transformation of various industries. The bioeconomy, driven by bio-based innovations, offers opportunities to address pressing global challenges, such as resource depletion, climate change, and food security. This section presents the overll findings of the bioeconomy's potential development based on the findings from the technology field assessments.

As indicated in section 2.1 innovations in the bioeconomy differ in type (e.g.process vs. product), degree of disruptiveness, sectors and impact path. Partially based on the developed classification of Bröring et al (2021) and Stark et al. (2022). Table 17 provides a rough attribution of the technology fields to those categorizations. For the transition pathways we add the increased provision of new / additional feedstock as the fifth potential pathway.

The chosen technology fields demonstrate diverse characteristics, with some focusing on process innovations while others on product innovations. Moreover, the impact of each technology field varied, encompassing economic, ecological, health, and other social dimensions. The potential disruptiveness of these innovations also differed, with some technology fields substituting existing products and processes with improved alternatives, while others may lead to broader value chain disruptions.

Table 17: Characterization of the Technology Fields

Technology Field	Sector	Disruption	Innovation type	Transition Pathway
Carbon Capture and Use (CCU)	Many manufacturing sectors	**rather high,** may provide large-scale substitution of fossil resources or biomass as carbon feedstock	Substitute products	n.a New/additional feedstock sources.
Alternative proteins	Food and Feed	**High**; substitution of meat production and industrial livestock "farming" possible with less need of biomass; Germany: meat production challenged	Substitute products	Increases in biomass use efficiency and new biomass uses:
Biopharmaceuticals	Pharmaceuticals	**Medium to high**; completely new kind of therapeutic, potentially better health effects	New products	Bio-based value added in low-volume/ high-value indus- tries:
Innovative wood products	Many manufacturing sectors	**Medium to low**, mainly substitution	Substitute products	Increases in biomass use efficiency and new biomass uses:
Bio-based plastics	Plastics	**Medium to low**, partly substitution, partly innovative non drop-ins	Substitute products	Substitution of fossil- by bio-based resources:

Bio-based surfactants	Chemicals	**Medium to low**, Second generation bio-based surfactants may enhance product performance and broaden range of applications	Substitute products / new products	Bio-based value added in low-vol- ume/ high-value industries:
Agriculture 4.0	Primary Pro- duction	**Medium,**, key enabling technologies for the bioeconomy	New proces- ses	Increases in pri- mary sector productivity:
Indoor Vertical Farming	Primary Pro- duction	**Low to medium,** potential to establish new plant production practices and value chains	New proces- ses	New/additional feedstock sources
Algae	Primary Pro- duction	**Low to medium**. biomass production not requiring arable land and biomass as carbon and energy source	Substitute Products /new Products	New/additional feedstock sources
Plant breeding	Primary Pro- duction	**Low to medium,** technological potenti- al, but /legal hurdles high	New proces- ses	Increases in pri- mary sector productivity:
Biotechnology	Primary Pro- duction, in- dustry and services	**High**, key enabling technologies for the bioeconomy for many sectors[60]	All innovation types	All paths
Microbiome	Primary Pro- duction, Food, health and environ- mental ser- vices	**Medium to high,** ability to engineer microbiomes is an emerging key ena- bling technology within biotechnology	New products	Bio-based value added in low-vol- ume/ high-value indus- tries:

For all of these technology fields considerable growth can be expected. The market drivers and barriers show rather high similarities across the technology fields. In many fields technological progress is directed towards the provision of more sustainable products and processes compared to existing ones. However, technological development is often still not mature, costs are usually higher than for existing fossil-base/chemical products, market regulation is providing little incentive (e.g. bio-based plastics), or even hinders change. Moreover, for some technology fields, consumers or the public are reluctant (e.g. biotechnology, bio-based plastics, plant engineering.

Many technology fields demonstrate high impact potential. Generally, bioeconomy's potential development aligns well with the United Nations' Sustainable Development Goals (SDGs). Various technology fields contribute to achieving specific SDGs, such as zero hunger (through alternative proteins and indoor vertical farming), climate action (via carbon capture and use, algae, and bio-based plastics), and sustainable industry and innovation (via biopharmaceuticals and biotechnology). Many technology fields show potential for market disruption, challenging conventional practices and fostering a shift towards bio-based alternatives. Here the broader technology fields of agriculture 4.0 and Biotechnology comprise a broad set of technologies that have key enabling character for the bioeconomy. The fields of Alternative Proteins and CCU have the potential for large changes in values chains and to substitute traditional products with potentially better environmental performance. Finally, biopharmaceuticals can lead to completely new kinds of therapeutics, with potentially better health effects. However, the realization is of course highly uncertain and

[60] Biotechnology may not be disruptive for every sub-field or individual sectors, but in total it may lead to disruptions to the economy

ambiguous as not in all dimensions only positive effects can be expected, and significant negative effects cannot be ruled out. In trend, potential high impact could be realized by CCU, Agriculture 4.0, Biotechnology, Alternative Proteins and biopharmaceuticals. Those impact may relate to a significant higher provision of feedstock (e.g. CCU, Agriculture 4.0) or higher efficiency leading to a relative reduction of biomass demand for certain production (e.g. alternative proteins) or economic impact (e.g. biotechnology, biopharmaceuticals). Rather limited effects for Germany are expected for example for algae or plant breeding as significant domestic production in Germany is unlikely because of economic or regulatory issues and cultivation and processing more likely taking place elsewhere .

Moreover, it has to be noted that there is significant degree of synergy and complementarity among the 12 technology fields. Many innovations contribute to multiple sectors, reinforcing the bioeconomy's interconnectedness. For instance, the advancements in biotechnology offer benefits across agriculture, healthcare, and industrial applications, while innovative wood products promote sustainability in forestry and manufacturing. This synergy enhances the overall impact of the bioeconomy and facilitates the transition towards a circular and sustainable model.

Patents and publication trends

Overall, the analysis of publications reveals mostly strong growth across all technology fields. Deviating patterns from this will be outlined in the following. Germany's share slightly declined over time and is currently between 3-8% of world-widepatents. Compared to other Countries, Germany has a high share in biopharmaceuticals and microbiomes and the lowest for bio-based surfactants and alternative proteins. Instead, technological competitiveness measured by patents differs stronger across technology fields, some emerging fields are significantly increasing in patents, such as alternative proteins and vertical farming. Other more mature technologies stagnating or decreasing, like biopharmaceuticals and biotechnology. Germany remains rather strong in technological competitiveness across all fields, with a substantial share in EU patents, which lies for some technology fields above 40%. Worldwide, the U.S. is leading in all technology fields[61], while China, coming from a rather low, is strongly catching-up in the last five years

In terms of specific technology groups, there are various trends to note. Carbon Capture and Use rises sharply in publications from 2019-2020, while alternative proteins had a sharp rise in both publications and patents since 2018. Biopharmaceuticals had high growth in publications since 2019, but a slight decrease in patents. Innovative wood products and bio-based plastics had a steady increase in publications, while bio-based surfactants just had a constant number of applications. Agriculture 4.0 saw a sharp rise in publications since 2016, while indoor vertical farming saw a sharp rise in publications since 2018, but with a declining share in Germany. Publications in algae slightly grew over time. Plant breeding had a stable growth in publications until 2005, then growing gradually. Biotechnology publications increased fluctuating, while microbiome saw occasional growth in publications and a significant increase in patents since 2010, with a highly varying share of EU patents in Germany.

[61] Measured on a country level, not compared to EU-27 in total

15.2 Limitations and boundaries of assessment

Unsurprisingly, quantitative, reliable information about potential impacts of the innovations is scattered. On the one hand, for almost all tech fields high sustainability potential is claimed by the proponents, but hardly any consideration of consequences of limited (biomass) resources is discussed / analyzed in detail by them. On the other hand critical reviewers (e.g. coming from NGOs, sustainability research, etc.) of such technology-centered vision of the bioeconomy are concerned about the environmental impact of a further increase and further industrialization of land uses as well of potential risks of such technologies. However, they are hardly referring to a specific technology. We tried to reflect those critical views for the discussion of the single technology fields, but it was beyond the scope of this report to discuss all potential detrimental effects on the macro-level for each technology case.

In addition, please note that regarding future developments for some technology fields are in particular uncertain as they would imply more radical change and various economic, societal and political factors influence those developments highly. And this is especially the case for those technology fields that have the highest claimed potential. For those market adoption (CCU, microbiome) is most uncertain.

Concerning the publication and patent analysis, please note that the technology different are in a different maturity stage, and some technology fields have rather many patents (e.g. bio-based surfactants) as there is tradition to use renewable feedstock for various applications and still some incremental advanced and still some patents applications are made and directly identifiable in International patent Codes. Instead, other technology fields are narrower and only identifiable by keywords, which usually lead to a lower number of results. Or in some cases, as for microbiomes health applications are probably majorly contributing to patent applications, but are of less relevance for this bioeconomy monitoring. Therefore, a direct comparison between the technology fields should be done with caution and hence we only summarize general trends and some reasonable examples.

15.3 Implications for Policy and Decision-making

The assessment of the 12 technology fields in the bioeconomy has provided valuable insights into the transformative potential as well as drivers and barriers of bio-based innovations. These findings carry relevant implications for policy and decision-making at the national and international levels.:

Policy activities play a critical role in creating an enabling environment for bio-based innovations to flourish. To promote investment in research and development, governments may establish supportive regulatory frameworks that incentivize private sector involvement. This includes e.g. providing funding opportunities and tax incentives to further support technological progress and innovation activities as well as streamlined approval processes for bio-based projects. At the same time, regulatory landscape has to consider issue of social acceptance for some technologies, as well as to ensure sustainability and circularity, encouraging the adoption of bio-based alternatives over fossil-based counterparts. In particular biomass is a critical resource in the bioeconomy, and its sustainable management is paramount to its success. Hence, policy actors should develop strategies for responsible biomass production, considering land use, biodiversity conservation, and carbon sequestration. Encouraging the use of non-food feedstocks and implementing circular approaches to biomass utilization will mitigate potential negative ecological impacts.

While most tech field assessment mostly focused on single sectors, it has to be considered that the bioeconomy's potential development is inherently cross-sectoral, with innovations spanning agriculture, healthcare, chemicals, and more. Policymakers may encourage collaboration and knowledge exchange between different sectors to maximize synergies and avoid duplication of efforts. Public-private partnerships, research consortia, and knowledge-sharing platforms can facilitate this collaboration and accelerate the bioeconomy's growth.

As novel technologies and approaches arise in the bioeconomy, there is a need for a skilled workforce to drive its implementation. Investment in education and skills development programs to equip the current and future workforce with the necessary expertise in biotechnology, digitalization, and other bio-based technologies.

Moreover, while it was beyond the scope of the technology field assessment to assess global and societal issues of the bioeconomy in general, these issues have to be considered as well. Technology transfer and knowledge exchange between countries and regions are essential for global bioeconomy development. Policymakers may facilitate international cooperation, promote technology transfer agreements, and support research collaboration to accelerate the deployment of bio-based innovations globally. This will create a more interconnected and resilient bioeconomy.

In addition, policymakers may consider the social dimensions of the bioeconomy's development to ensure inclusivity and social equity. Investments in bio-based innovations may be designed to benefit all segments of society and address socio-economic disparities.

In conclusion, the implications for policy and decision-making derived from the assessment of the 12 technology fields underscore the need for a comprehensive and integrated approach to harness the full potential of the bioeconomy. Strategic policy interventions, collaborative initiatives, and sustainability-oriented frameworks will pave the way for a thriving and sustainable bioeconomy, contributing significantly to global efforts in tackling pressing challenges and achieving a more resilient and prosperous future.

15.4 Case Studies for In-depth Assessment

The comprehensive assessment of the 12 technology fields in the bioeconomy has provided valuable insights into their potential impact and transformative nature. To gain a deeper understanding of the real-world implications of these technology fields and to explore their connection to the modeling efforts in Symobio 2.0, four case studies have been selected for in-depth analysis. These case studies aim to shed light on the specific nuances, challenges, and opportunities presented by each technology field, providing essential information for policymakers, researchers, and stakeholders.

Meat Alternatives: The case study on meat alternatives can delve into the rapidly growing sector of protein-rich foodstuffs designed to replace conventional meat products. Such case study can focus on plant-based meat alternatives and provides a view into the potential disruptive impact of these alternatives on the food industry. By examining the development paths, potential drivers, and projected economic, ecological, and social impacts, the case study can aim to reveal the opportunities and challenges in transitioning to more sustainable and resource-efficient food systems. Additionally, it can explore the links between the diffusion of meat alternatives and key parameters in Symobio 2.0's modeling, providing valuable insights for scenario analyses and policy recommendations.

Artificial Intelligence (AI) in Agri-food Systems: The AI in agri-food systems case study can explores the implementation of artificial intelligence technologies, such as machine learning and data analytics, throughout the agri-food value chain. Such study can assess how cutting-edge AI applications can enhance efficiency and innovation in a selected sector/field in Germany. By investigating the economic, ecological, and social impacts of AI advancements in agri-food systems, the case study can provide a deep understanding of the potential benefits and trade-offs associated with AI deployment. Moreover, it may examine the integration of AI insights into Symobio 2.0's modeling, enriching the scenario analyses and contributing to more informed policy recommendations.

Biopharmaceuticals: The biopharmaceuticals case study explores the potential transformative impact of biopharmaceutical research and production on the healthcare industry and society's health outcomes. By analyzing innovation patterns, key deployment factors, and indicators of competitiveness, the case study can highlight Germany's position in the biopharmaceutical sector. Additionally, it assesses the implications of biopharmaceutical advancements on economic growth, ecological sustainability, and public health.

Bio-based Surfactants (2nd Generation): The case study on 2nd generation bio-based surfactants can investigate the production of surface-active compounds derived from biomass through fermentation processes. By examining innovation patterns, key drivers, and indicators of technological competitiveness, such study can offer insights into the successful deployment of bio-based chemicals. The case study may identify lessons learned from the bio-based surfactants' deployment that may apply to other product groups within the bioeconomy. Moreover, it can further explore the potential replicability of the refined and extended innovation indicators for other segments. The case study can contribute to a better understanding of how technological advancements in specific bio-based sectors can drive sustainable economic growth and environmental benefits.

All in all, the four case studies selected for in-depth assessment can help to gain a deeper understanding of the transformative potential and impacts of specific technology fields within the bioeconomy. By focusing on these cases, the assessment report can inform Symobio 2.0's modeling, enriching the scenario analyses and contributing to more informed policy recommendations.

The case studies will partly build up on the technology field sheets and extend them .For all case study literature insights on impacts will be synthetized. In addition they will address different issues of measurement of emergence, deployment and impact of innovation (Table 18). The technology field assessment clearly revealed that in some cases a more concrete focus is needed so a modified delineation for case studies was considered as well. These present very different innovations (products vs. processes) in quite different sectors of the bioeconomy. The reasoning and relevant research questions are listed in Table 17.

The outcomes of such case studies can contribute to the overarching goal of building a more resilient and efficient bioeconomy in alignment with sustainability objectives in Germany, EU and beyond.

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16 Appendix

Table 18: Selected case studies

Title	Technology field definition Scope	Criterion I: Relevance	Criterion 2: Suitability for analysis	Main research Questions
Meat Alternatives	Protein-rich foodstuffs to replace conventional meat products in terms of organoleptics. (Focus on plant-based Meat Alternatives as those may have the largest impact in next 10-20 years and a little outlook on Cultivated Meat as potentially relevant innovation in long-term)	High- and low-tech solutions that could significantly reduce biomass and land use for animal feed, reduce other negative environmental impacts and alleviate animal welfare issues of livestock production.	There are potential links to model approaches possible as alternative meat alternative diffusion may have a significant impact on these variables Emerging Literature is available that analyses potential impact	What are potential development paths and related drivers for plant-based meat alternatives and cultivated meat) What are the projected economic, ecological, and social impacts (synthesis of literature)? Which model parameters (e.g. of GLORIA) can be affected by the diffusion of Meat Alternatives? What could be the future range of estimable parameters (BAU-Scenario +potential drivers and their impacts? What would be future steps to improve congruency to modelling exercise?
Artificial Intelligence (AI) in agri-food systems	AI in agri-food systems encompasses the implementation of artificial intelligence technologies, such as machine learning, data analytics, and sophisticated algorithms, to streamline processes and enhance decision-making throughout the entire agri-food value chain.	AI in agri-food systems has the potential to increase efficiency, sustainability, and innovation across the entire value chain, from primary production to processing, distribution, and consumption.	AI's widespread implementation in agri-food systems, driven by its capacity to process and analyze rich, real-time data, makes it a suitable focus for exploring efficiency, sustainability, and innovation across various sectors.	How are the latest advancements in AI tools and models transforming agri-food systems, and what are the key factors driving their wide adoption? What are the potential economic, ecological, and social impacts of cutting-edge AI applications in agri-food systems, and how do they differ from traditional practices? How can we develop robust indicators to assess the impact of AI technologies in agri-food systems, considering the dynamic nature of AI advancements? How can insights from AI advancements in agri-food systems be integrated into the interpretation of SymoBio modeling results to enhance scenario analyses and inform more effective policy recommendations?

Biopharma	large molecules from biological sources, which are a class of protein based drugs (e.g. hormones, antibodies)	new kind of therapeutics with potentially better health effects; Biopharmaceutical R&D and production bring high value added and high-skilled jobs	rather good availability of indicators and indicators	What kind of innovations are emerging until 2030/2040? What are key factors for wide deployment? What are suitable indicators to analyze innovation patterns? Do further refined and extended innovation indicators (publications, patent data, firm data, employment estimations) show a consistent picture? How is the competition situation of Germany? is technological sovereignty given?
Bio-based surfactants (2nd generation)	Surface-active compounds that are wholly or partly derived from biomass and produced by fermentation	Direct market size limited; but biosurfactants second generation surfactants as showcase of potential impact of biotech innovations	Segment can be rather well delineated in terms of innovations. Bio-based surfactants can be considered as flagship product group for successful deployment of bio-based chemicals that may provide insights / lessons for other product groups	What kind of innovations are emerging until 2030/2040? What are key factors for wide deployment? Which innovation patterns can be observed from redefined (focusing on 2nd generation biosurfactants) and extended innovation indicators (publications, patent data, firm data, employment estimations)? To which extent would those indicators be replicable for other segments?

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