Monitoring Innovations in the Bioeconomy -

Insights from Case Studies for Alternative Meat, Bio-Based Surfactants, Biopharmaceuticals, AI in Regenerative Agriculture

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Monitoring Innovations in the Bioeconomy - Insights from Case Studies for Alternative Meat, Bio-Based Surfactants, Biopharmaceuticals, AI in Regenerative Agriculture

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Notes

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Abbreviations

Abbreviation	Full name
AI	Artificial Intelligence
API	Active Pharmaceutical Ingredient
ADC	Antibody-Drug Conjugate
B2B	Business-to-Business
B2C	Business-to-Consumer
BAU	Business as usual
BCG	Boston Consulting Group
BMBF	Federal Ministry of Education and Research of Germany
BMEL	Federal Ministry of Food and Agriculture of Germany
CAGR	Compound Annual Growth Rate
CEN	The European Committee for Standardization
CHO	Chinese Hamster Ovary
CM	Cultivated Meat
DNA	Deoxyribonucleic Acid
D&I	Development and Innovation
EC	European Commission
EEA	European Environment Agency
EFI	German Expert Group on Research and Innovation
EIT	European Institute of Innovation and Technology
EMA	European Medicines Agency
ERA	Environmental Risk Assessment
EU	European Union
EU27	27 countries of the European Union
GHG	Greenhouse Gas
GLORIA	GLObal Resource Input-output Assessment
HLB value	Hydrophilic-Lipophilic Balance value
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communication Technology
IPC	International Patent Classification
$kgCO_2eq$	Kilogram of carbon dioxide equivalent
kta	Kilo tons per annum
LCA	Life Cycle Assessment
LLM	Large Language Model
LPs	Lipopeptides
mAbs	Monoclonal Antibodies
MELs	Mannosyl Erythritol Lipids
ML	Machine Learning
MRIO	Multi-Region Input-Output

NLP	Natural Language Processing
NME	New Molecule Entities
PBMA	Plant-Based Meat Alternative
R&D	Research and Development
RLs	Rhamnolipids
RNA	Ribonucleic Acid
SDG	Sustainable Development Goal
SLs	Sophorolipids
US	The United States
UK	The United Kingdom
WHO	World Health Organization

1 Introduction

1.1 Background

While the evolution and impacts of the bioeconomy depend on many interdependent factors, technological innovations play a crucial role in enabling contributions to the bioeconomy on the economy, environment and human well-being, or mitigating unintended impacts. Therefore, especially for a prospective outlook, analysing technological innovations is essential to better understand the likely pathways and effects of the bioeconomy.

For that purpose, the Symobio 2.0 project adopts a two-stage approach to analyse innovations. First, a screening and initial assessment of selected technology fields was conducted, focusing on their innovativeness, prospective development, and potential impacts (Wydra et al., 2023). Second, based on these insights, four case studies were selected and more concretely defined, followed by in-depth analysis. This report presents the results of the four in-depth assessments (chapters 2 to 5) and provides overarching conclusions across the case-studies (chapter 6).

1.2 Objective and approach

The aim of the in-depth analyses is to gain a deeper understanding of the potential implications of these technology fields and to explore their connection to quantitative approaches, which are central to Symobio 2.0. The case studies aim to shed light on the specific nuances, challenges, and opportunities for each technology field, providing essential insights for policymakers, researchers, and stakeholders.

To achieve this, initial selection criteria and qualitative considerations were defined to further specify the case studies. The first criterion was "relevance", focusing on the direct or signalling impact of the technology on the development of the bioeconomy. Second criterion was "suitability for analysis", which referred primarily to the potential for gathering additional insights and the availability of quantitative information to further support the overall quantitative assessment of innovations. In addition, the portfolio of case studies was designed to present diverse types of innovations (e.g., products versus processes) across different sectors of the bioeconomy. The selected case studies are as follows (see Table 1 for their suitability to the criteria):

- Meat alternatives
- Biopharmaceuticals
- Bio-based surfactants (second-generation)
- AI for regenerative agriculture

For each case study, a description of the technology is followed by an in-depth assessment of innovation and economic data on current developments (e.g., firms, production value, market data) as well as drivers and barriers. Subsequently, the economic, ecological, and in some cases, other impacts are assessed. Although the analysis framework was uniform for all case studies, the type of data, level of detail, and therefore the specific research questions vary depending on the availability of information sources and the specific focus of each case study: In the case of the *biopharmaceuticals*, the analysis focusses on the potential environmental impacts, whereas for *meat alternatives*, the link to modelling approaches applied in SYMOBIO2.0 is a key focus. For *AI in regenerative agriculture*, the scarcity of existing data led to the use of an online survey to gain qualitative, expert-based insights. Finally, for *second-generation biosurfactants*, firm-level data was collected and analysed. The main research questions are presented in Table 1.

Methodologically, the case studies build upon the technology field screenings (Wydra et al., 2023) and extend them. For all case studies, literature insights on impacts were synthetized, and statistical data was explored to provide a comprehensive understanding.

In the following we first present the four case studies (chapters 2 to 5), each with case study specific conclusions. The final chapter 6 provides overall conclusions from the case studies on innovation pathways and structural challenges shaping the further development of the bioeconomy.

Table 1: Selected case studies

Title	Technology field definition and scope	Criterion 1: Relevance	Criterion 2: Suitability for analysis	Main research questions
Meat alternatives	Protein-rich foodstuffs to replace conventional meat products in terms of organoleptic properties. The focus is on plant-based meat alternatives, as these are expected to have the largest impact over the next 10-20 years, with a brief outlook on cultivated meat as potentially relevant long-term innovation.	High- and low-tech solutions are explored that could significantly reduce biomass and land use for animal feed, mitigate other negative environmental impacts of livestock farming, and alleviate animal welfare issues in livestock production.	There are potential links to modelling approaches, as the diffusion of alternative meat products could significantly impact these variables. Emerging literature is available that analyses their potential impact.	What are potential development paths, and what are the related drivers and barriers for plant-based meat alternatives and cultivated meat? What are the projected economic, ecological, and social impacts (based on a synthesis of literature)? How can the diffusion of meat alternatives be analysed in modelling exercises? What could be the future range of estimable parameters under a BAU-Scenario, including potential drivers and their impacts? What would be the future steps to improve alignment with modelling exercises?
Artificial Intelligence (AI) in regenerative agriculture	Application of artificial intelligence technologies to enhance, support, and optimize regenerative agricultural practices that focus on restoring soil health, increasing biodiversity, improving water retention, and promoting sustainable farming systems	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.	Focusing on AI in regenerative agriculture provides a practical and suitable approach for analysis within the broader context of digitalization in agriculture, with feasible methods such as surveys to gather insights.	What are the latest advancements in AI tools and models transforming agri-food systems? What are the key factors driving the widespread adoption of these technologies? What are the potential economic, ecological, and social impacts of cutting-edge AI applications in agri-food systems (based on online survey)? How do these impacts differ from those of traditional practices?
Biopharma	Large molecules derived from biological sources, representing a class of protein-based drugs (e.g., hormones, antibodies)	The development of a new kind of therapeutics holds the potential to improve health outcomes, while biopharmaceutical research, development, and production contribute significant value to the economy and create high-skilled employment opportunities.	A relatively good availability of indicators and data sources ensures the analysis suitable and feasible.	What is the market outlook for biopharmaceuticals and what are key factors for wide deployment? What are suitable indicators to analyse innovation patterns? What are the projected economic and particularly ecological impacts (synthesis of literature)?

Title	Technology field definition and scope	Criterion 1: Relevance	Criterion 2: Suitability for analysis	Main research questions
Bio-based surfactants (2nd generation)	Surface-active compounds derived wholly or partly from biomass and produced via fermentation	The direct market size for bio-surfactants may be limited; however, 2nd generation bio-surfactants serve as a compelling example of the 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 is the market outlook for 2nd generation bio-based surfactants, and what are key factors for wide deployment? Which innovation patterns can be observed based on economic indicators (e.g., firm data, employment estimations)? To which extent would those indicators be replicable for other segments? What are the projected economic, ecological, and social impacts (synthesis of literature)?

2 AI and regenerative agriculture

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2.1 Introduction

2.1.1 Overview of AI in agriculture

Agriculture, traditionally driven by generations of farming knowledge and experience, is undergoing a transformation with the rise of new technologies. Among these, artificial intelligence (AI) is a key driver of change, playing a crucial role in domains like crop prediction, disease detection, and precision farming. By enabling more efficient and data-driven farming practices, AI provides potential to optimize resources, reduce waste, and improve productivity. However, while AI has been applied in conventional agriculture since several years, its potential in regenerative agriculture is gaining increasing attention as the demand for sustainable solutions grows.

Regenerative agriculture has recently emerged as a notable trend in sustainable farming, drawing interest from farmers, corporations, consumers, and policymakers alike. Seen by some as a movement, regenerative agriculture is increasingly being adopted worldwide, with countries like Brazil, India, and the USA dedicating large areas of land to regenerative methods (Newton et al., 2020). The approach focuses on enhancing soil health, restoring ecosystems, and promoting biodiversity, positioning it as a critical solution to challenges such as soil degradation, biodiversity loss, and climate change. The potential of regenerative agriculture to improve sustainability in food systems is widely recognized, making it an essential component of future farming strategies.

AI's role in regenerative agriculture goes beyond traditional applications like optimizing productivity. Its potential in regenerative agriculture lies in its ability to provide real-time insights and data-driven solutions that support long-term environmental goals. AI can help farmers optimize resource use, improve soil regeneration, track biodiversity, and adapt their practices to local ecosystems. Despite its potential, there remains a gap in understanding the extent to which AI has been applied in regenerative agriculture, to which extend expected impacts can be realized and what it may still be capable of achieving in the near future, as comprehensive analysis and empirical evidence on this intersection remain limited. To address this, we will collect information on both existing and emerging AI applications and conduct an online survey to gather insights from professionals involved in the research and development of AI or regenerative agriculture. This approach aims to better understand how AI is currently being utilized and its future potential to further support regenerative practices.

2.1.2 Definition of AI and regenerative agriculture

2.1.2.1 Definition of AI

Definition of Artificial Intelligence, as proposed within the European Commission’s Communication on AI (European Commission, 2018b):

"Artificial intelligence (AI) refers to systems that display intelligent behaviour by analysing their environment and taking actions – with some degree of autonomy – to achieve specific goals.

AI-based systems can be purely software-based, acting in the virtual world (e.g. voice assistants, image analysis software, search engines, speech and face recognition systems) or AI can be embedded in hardware devices (e.g. advanced robots, autonomous cars, drones or Internet of Things applications)."

To avoid misunderstanding and to foster a shared understanding of AI, including among non-experts, the Independent High-Level Expert Group on Artificial Intelligence, established by the European Commission, proposed an updated definition (European Commission, 2018a):

"*Artificial intelligence (AI) refers to systems designed by humans that, given a complex goal, act in the physical or digital world by perceiving their environment, interpreting the collected structured or unstructured data, reasoning on the knowledge derived from this data and deciding the best action(s) to take (according to pre-defined parameters) to achieve the given goal. AI systems can also be designed to learn to adapt their behaviour by analysing how the environment is affected by their previous actions.*

As a scientific discipline, AI includes several approaches and techniques, such as machine learning (of which deep learning and reinforcement learning are specific examples), machine reasoning (which includes planning, scheduling, knowledge representation and reasoning, search, and optimization), and robotics (which includes control, perception, sensors and actuators, as well as the integration of all other techniques into cyber-physical systems)."

2.1.2.2 Definition and significance of regenerative agriculture

Although regenerative agriculture lacks a universally accepted legal or academic definition, it is broadly understood in a consistent manner. BCG (2023) describes it as "an adaptive farming approach that applies practically proven and science-based practices, focusing on soil and crop health to enhance yield resilience and positively impact carbon, water, and biodiversity". Similarly, Schreefel et al. (2020) define it as "a farming approach that uses soil conservation as the entry point to regenerate and contribute to multiple ecosystem services".

These definitions align with the concept of regenerative agriculture as recognized in the EU. The European Institute of Innovation and Technology (EIT) has outlined five key principles of regenerative agriculture (EIT Food, 2020):

- Minimizing soil disturbance
- Minimizing the use of chemical inputs
- Maximizing biodiversity, both animals and plants
- Keeping the soil covered with crops as long as possible
- Adapting to the local environment

This approach is regarded as a sustainable alternative to conventional farming, playing a crucial role in addressing global challenges such as climate change, biodiversity loss, and the growing demand for healthier, more sustainable food (Muhie, 2022), all while ensuring adequate food production (BCG, 2023; EIT Food, 2020). As awareness of climate change continues to rise, the environmental benefits of regenerative agriculture are increasingly being recognized. However, the question of whether regenerative agriculture can match the food production levels of conventional farming remains a topic of debate. In this context, EIT Food notes that long-term side-by-side field studies suggest that after an initial one-to-two-year transition period – during which yields may decline – there is no significant difference in yields between conventional and regenerative farming (EIT Food, 2020). Furthermore, under challenging conditions, particularly during droughts, regenerative fields tend to perform better due to their enhanced resilience, as their soils can absorb more water thanks to higher biomass content (EIT Food, 2020). BCG also argues that regenerative agriculture can safeguard future food supplies by better responding to climate-related system shocks (BCG, 2023).

Manshanden et al. (2023) point out that regenerative agriculture focuses on outcomes, and the path to achieving these outcomes can vary for each farmer. However, there are several practices commonly recognized as typical of regenerative agriculture. They are listed in Table 2.

Table 2: Typical practices associated with regenerative agriculture

Practice	Description
No-till practices	Methods such as direct seeding that minimize or eliminate soil disturbance by tilling machinery.
Subsoiling	Minimally disturbing soil breakup below the surface to reduce soil compaction.
Cover cropping	Growing diverse plant groups on croplands that would conventionally be left fallow during parts of the year.
Soil analysis and balancing	Using nutrient checks and balancing (e.g., Haney/Kinsey test) to avoid overfertilization and improve soil health.
Interseeding and undersown cropping	Enhancing existing cover on pastures and simultaneously growing secondary crops alongside main crops for better soil cover.
Biofertilizers and biostimulants	Utilizing biofertilizers made predominantly from farm biomass, including compost, to enhance biodiversity and nutrient management.
Bio leaching inhibitors and bio crop protection	Developing biological solutions to reduce nitrate leaching and employing nonsynthetic crop protection methods.
Legume crop rotation and intercropping	Integrating legumes into the main crop cycle and cultivating multiple crop species in a single field.
Biologically activated biochar	Applying biochar activated with microorganisms to fields as a by-product of biomass burned in the absence of oxygen.
Smaller aerial structures and livestock integration	Breaking up large monoculture fields into smaller segments and temporarily introducing livestock onto croplands for grazing or crop rotation.
Agroforestry practices	Incorporating trees, hedges, and shrubs into cropland and grassland.
Other practices	Including keyline subsoiling, grassland pasture cropping, and methods to reduce soil erosion.

Source: Khangura et al. (2023), The Food and Land Use Coalition (2023), PhycoTerra (2020)

2.1.3 Aim of the case study

The primary objective of this study is to explore the potential of Artificial Intelligence (AI) technologies in regenerative agriculture in Germany. As agriculture faces multiple challenges, such as resource scarcity, a shortage of skilled labour, and environmental protection (Geppert et al., 2024), AI technologies are expected to play a key role in addressing these issues by improving productivity, optimizing resource use, and enhancing agricultural sustainability. This study will analyse the specific applications of various AI technologies in agriculture, particularly in crop management, soil health monitoring, and pest control, to assess their potential contribution to the future sustainability of agriculture.

In addition, the study aims to evaluate the broader impact of AI technologies on regenerative agriculture. Beyond exploring the direct benefits of AI, it will focus on analysing potential barriers to its adoption, including the cost of the technology, access to data, farmers' adaptive capacity, and relevant policy frameworks. By examining these challenges and opportunities, the study seeks to offer insights into how AI technologies can be effectively integrated into agricultural practices and provide policy recommendations to promote regenerative agriculture in Germany and globally.

Existing research has primarily focused on the development of AI technologies, particularly the innovation and experimentation of different AI technologies across various agricultural applications. As a result, the relevant literature is rather fragmented. Although it covers a wide range of technological fields, it lacks a systematic analysis of AI's role in regenerative agricultural practices. Specifically, there is very limited literature dedicated to exploring the potential and impact of AI in regenerative agriculture in Germany, leading to an incomplete understanding of the technology's full scope in practical agricultural contexts.

Considering this limitation, we designed an online survey to collect empirical data. The survey targeted experts and professionals in AI and agriculture, with questions covering the current use of AI technologies, barriers to adoption, and their perceived effectiveness in enhancing sustainability. Participants were asked to rate AI's impact on soil health, biodiversity, and carbon sequestration, and provide insights into regulatory and financial challenges. This approach allowed us to gather expert perspectives on the potential role of AI in regenerative agriculture in Germany. By analysing these responses, we aim to fill gaps in the existing literature and provide a more systematic understanding of AI's applications in regenerative agriculture.

2.2 AI in regenerative agriculture: status-quo and outlook

2.2.1 Overview of AI in regenerative agriculture

As artificial intelligence (AI) technology advances, its application in both traditional and regenerative agriculture is growing rapidly. While the core AI techniques – such as machine learning – are the same in both contexts, the ways in which they are applied vary significantly. This variation is primarily due to the different goals of these agricultural approaches. In regenerative agriculture, AI is often used to promote environmental sustainability and support regenerative practices, whereas in traditional agriculture, the emphasis is generally on boosting productivity and efficiency. In essence, the distinction in AI application comes down to whether the technology aims to achieve regenerative environmental goals or enhance conventional agricultural outcomes. However, in the future it might be worthwhile to explore whether and how both goals could be combined.

In traditional agriculture, AI is primarily used to automate and optimize processes to increase productivity, reduce human labour, and ensure operational safety (European Parliament, 2023). Key examples include automated harvesting, predictive maintenance of machinery, and labour optimization.

In regenerative agriculture, AI applications are more varied and nuanced. For instance, automated feeding systems may initially appear to simply optimize the feeding process and save human labour. However, by applying reinforcement learning, these systems can learn from interactions with the environment – such as animal behaviour and feeding outcomes – to optimize feeding strategies. This approach can potentially reduce feed waste and help ensure animals receive the appropriate nutrients at the right time, which may contribute to better animal health and reduce the need for antibiotics or other interventions, aligning with regenerative practices. Detailed AI applications in regenerative agriculture and the AI techniques involved are summarized in Table 3. It is worth noting that the applications included in Table 3 are those mentioned in the literature as either possible or realized applications.

AI techniques refer to a range of methods used to develop artificial intelligence systems. In regenerative agriculture, machine learning is the most commonly applied type of AI. It is important to note that "machine learning" is a broad field that encompasses various algorithms and models designed to learn from numerical, textual, and image-based data (IBM, 2024b). However, in practice, it often specifically refers to techniques that are particularly effective for analysing numerical input data and uncovering patterns behind the data. In regenerative agriculture, applications involving predictions based on collected or historical data almost always rely on machine learning.

Other common AI techniques include deep learning and computer vision. These techniques are often used together to process image data. While deep learning, which involves the use of neural networks with many layers, is particularly effective at modelling complex patterns in data with increasing accuracy, it can also process various types of data beyond just images (IBM, 2024a). For instance, deep learning and computer vision are frequently applied to analyse soil images or to identify plant diseases and pests based on visual data.

Another increasingly popular AI technique is natural language processing (NLP), with one of its most famous applications being chatbots, such as ChatGPT. In regenerative agriculture, NLP can be combined with other AI techniques to answer farmers' questions based on data predictions or images provided by the farmer.

Table 3: Potential and actual applications of AI techniques in regenerative agriculture

Application fields	**Details**	**Involved AI techniques**
Precision farming (Siemens, 2024; Goedde et al., 2020)	Variable Rate Application: Adjusting seed planting rates, fertilizer application rates, and irrigation levels based on real-time data and predictive models.	Machine learning
	Smart Irrigation Systems: Using AI to schedule irrigation based on soil moisture levels, weather forecasts, and crop water requirements to optimize water use efficiency.	Machine learning
	Precision Fertilizing: Optimizing fertilization using AI models based on localized variations in soil nutrient levels, crop requirements, and environmental conditions.	Machine learning
Soil health and management (European Parliament, 2023)	Soil Nutrient Analysis: Predicting nutrient deficiencies and recommending appropriate fertilizers using AI models based on soil test data.	Machine learning
	Soil Moisture Monitoring: Optimizing irrigation schedules by using sensor data and ML algorithms to ensure crops receive the optimal amount of water.	Machine learning
	Disease Detection: Analysing soil samples to detect pathogens and predict the likelihood of disease outbreaks.	Machine learning, computer vision
Climate adaptation and resource management (European Parliament, 2023)	Water Management: Using AI to analyse soil moisture data and weather forecasts to optimize irrigation schedules, reducing water use while maintaining crop health.	Machine learning
	Climate-Responsive Planting: Predicting optimal planting times and crop varieties using AI based on expected climate conditions to maximize yield stability.	Machine learning
	Carbon Sequestration: Monitoring and managing cover crops and crop rotations using AI to enhance soil carbon storage and mitigate climate impacts.	Machine learning
Integrated decision-making (Bayer, 2024a; Chandolikar et al., 2022; Itzhaky, 2021)	Chatbots: Leveraging AI technologies to provide farmers with timely and accurate information, support decision-making, and enhance productivity.	Natural language processing, machine learning

Application fields	Details	Involved AI techniques
Plant health monitoring (European Parliament, 2023; Tirkey et al., 2023)	Plant Disease Detection: Using AI models trained on images to identify diseases early in plants, allowing for timely intervention.	Computer vision, deep learning
	Pest Monitoring: Using AI to analyse visual signs of pest activity and predict outbreaks based on environmental conditions and historical data.	Computer vision, deep learning, machine learning
	Stress Detection: Monitoring changes in plant physiology and environmental stressors to predict and mitigate the impact of drought, heat, or cold stress.	Machine learning, deep learning, computer vision
	Nutrient Deficiency Identification: Analysing leaf colour and texture using AI systems to diagnose nutrient deficiencies and recommend corrective measures.	Computer vision, deep learning, machine learning
Weed detection and management (Vasileiou et al., 2024; Vijayakumar et al., 2023; BASF, 2020)	Selective Herbicide Application: Using AI systems to identify weed-infested areas and control spraying equipment for targeted herbicide application, minimizing chemical usage.	Computer vision, deep learning, machine learning
	Early Detection: Analysing environmental data and early-stage weed growth using AI models to alert farmers about potential infestations before they become severe.	Machine learning, deep learning
	Weed Mapping: Creating detailed maps of weed distribution using drones equipped with AI, enabling targeted and efficient weed control measures.	Computer vision, machine learning, deep learning
Yield prediction (BASF, 2020)	Early Season Prediction: Using AI to predict yields shortly after planting based on initial growth patterns and environmental conditions.	Machine learning
Livestock management (European Parliament, 2023; Goedde et al., 2020)	Automated Feeding Systems: AI-controlled feeders adjusting feed quantities based on real-time nutritional requirements and animal behaviour.	Machine learning, reinforcement learning
	Animal Health Monitoring: AI-based systems detecting early signs of illness or injury through behavioural analysis and sensor data, enabling prompt intervention.	Computer vision, machine learning, deep learning
	Grazing Optimization: Calculating optimal grazing rotations using AI algorithms to maximize pasture health and minimize overgrazing, supporting sustainable land use.	Machine learning, reinforcement learning

Source: Own summary based on the different sources mentioned in the table above.

It is worth emphasizing that most AI applications mentioned in Table 3 are technically feasible, with some already being implemented in small-scale practices (Siemens, 2024; BASF, 2020), although these applications are continuously improved. Among the various applications of AI in regenerative agriculture, the two most important areas and their benefits are outlined below.

Precision Farming: AI is revolutionizing precision farming, a comprehensive concept that optimizes agricultural practices across multiple stages (World Bank, 2024). In smart irrigation systems, AI leverages soil moisture sensing and weather forecast data to predict and adjust irrigation levels accurately. This approach is supposed to minimize water usage while ensuring crops receive adequate water, while traditional irrigation methods often lead to over-irrigation by focusing solely on maximizing productivity. Since smart irrigation systems primarily rely on machine learning algorithms to process data and predict water consumption (a relatively straightforward technique within the AI family), the technology has advanced to the point where it is available on the market (Topraq, 2024; FarmERP, 2022). Additionally, AI-driven smart fertilization can analyse soil and crop data to develop precise nutrient plans, reducing fertilizer use while ensuring optimal crop nutrition (Siemens, 2024). In crop health management, AI is now capable of detecting and identifying pests through image recognition and reporting them to farmers (FieldRoutes, 2024; Rentokil, 2023). This capability helps farmers save time searching for pests, enables timely intervention, and can reduce pesticide use. However, AI-based solutions still require human intervention to eliminate pests after they have been identified.

Integrated Decision-Making in Agriculture: AI has the potential to enhance integrated decision-making in agriculture (Itzhaky, 2021). As agriculture becomes increasingly data-driven, large datasets encompassing soil conditions, meteorological information, and crop growth metrics are gradually becoming valuable inputs for analysis and prediction. A prominent application of AI in this field is bot advisory services (World Economic Forum, 2024). Bayer is establishing itself as a leader in this area. Leveraging internal agronomic data from the past decades and partnering with Microsoft, Bayer is training a Large Language Model (LLM), a subset of NLP techniques, to provide rapid and precise answers about farm management, agronomic conditions, and Bayer products (Bayer, 2024a; Bayer, 2024b). This AI tool has undergone pilot testing and shown improvements in productivity (Bayer, 2024b). Bayer also expects it to contribute to natural resource conservation, though specific details on this potential benefit have not yet been published (Bayer, 2024b). The implementation of this AI tool is set to expand to selected scientists and farms this year (Bayer, 2024b).

With these potentially impactful applications, integrating AI with regenerative agriculture are promising significant benefits. Economically, AI is expected to enhance crop yields and resource efficiency by optimizing farming practices and improving plant health, which may help reduce production costs. Environmentally, AI could refine irrigation and fertilization schedules, reduce water and chemical waste, and support land and water conservation efforts. Socially, AI has the potential to provide small and marginalized farmers with access to affordable and innovative solutions, address labour shortages through automation, and improve technical skills and social equity among farmers. These potential benefits highlight AI's role in supporting sustainable practices within regenerative agriculture.

However, amidst these advantages, a critical question arises: Are food growers adequately prepared to embrace and effectively utilize the array of new technologies and tools being developed for them (Itzhaky, 2021)? This question has a double meaning. On the one hand, it asks whether users, mainly farmers, are emotionally willing to accept AI technologies. The further adoption of AI technologies in agriculture requires that farmers and consumers trust the services offered (European Parliament, 2023). This trust determines whether they are willing to start using AI technologies. On the other hand, it asks whether they are capable of using AI technologies. Farmers who have never been trained in information technology will inevitably need specialized training to work with AI technology, although the introduction of virtual assistants and chatbots will make this easier. According to the European Parliamentary Research Service, policies for training and education must support potential users (European Parliament, 2023). This support is crucial for the successful and sustainable integration of AI with regenerative agriculture.

A more concerning outcome is that some farmers may attempt to adopt new technologies but fail to keep pace with the trends. After all, over one-third of EU farmers are over 65 years old, while less than 5% are under 35 years old (European Parliament, 2023). It is understandable that older farmers may find it challenging to adapt to technological changes. Another worrisome scenario is that farmers who strive to adapt to technological changes might still face unemployment risks (European Parliament, 2023). With tasks like planting, irrigation, soil testing, weeding, and harvesting becoming automated through AI technology in the future, will there still be a need for as much labour in agriculture? However, while there is indeed a risk of decreased labour demand due to the application of AI technology, the labour supply is also decreasing. In line with the data from the European Parliament, ING reports that as baby boomers age, they will leave a significant labour gap in agricultural occupations, with 35.6% over the age of 55 set to leave the labour market in the next 10 years (ING Think, 2024). Thus, the development of AI technologies can help mitigate the negative impact of this demographic shift, ensuring that agricultural productivity remains stable despite the reduced labour force.

Additionally, a key challenge in applying AI to regenerative agriculture is the data itself, which acts as a bottleneck (Vasisht et al., 2017). Since AI technology depends on data collected manually by farmers or automatically by sensors, the availability of this data is critical (European Parliament, 2023). Manual data collection is both time-consuming and labour-intensive. On the one hand, if farmers are tasked with recording data, it adds to their workload and requires additional training, as this responsibility falls outside their usual duties. On the other hand, employing professionally trained data collectors can significantly increase the overall cost of the process. Most importantly, human labour alone is insufficient to meet AI's growing demand for big data. Therefore, automating data collection is the sustainable solution. However, according to Microsoft, obtaining data from farms is extremely challenging due to often limited power in the field and weak internet connections in the farms (Microsoft, 2024). Even if these technical challenges were addressed, installing sensors for automated data collection would still be very expensive. Precision farming requires an accurate map containing information from all parts of the farm, such as soil temperature, soil moisture, and nutrient content (Vasisht et al., 2017). To build such a precise map, existing precision farming solutions require a dense deployment of ground sensors. As farms grow in size, the cost of dense sensor deployment increases, and management becomes more complex (Vasisht et al., 2017).

2.2.2 AI and regenerative practices in German agriculture

In Germany, the federal government expects to see developments in the digitalization of agriculture. The German Federal Ministry of Food and Agriculture (Bundesministerium für Ernährung und Landwirtschaft, BMEL), which is primarily responsible for this area, is highlighting Germany's strategy development for digitizing agriculture starting few years ago, and funding for these efforts began even earlier (BMEL, 2022a). Under this funding framework, there are five key areas of focus: digital experimentation fields, competence networks, feasibility studies for government digital data platforms for agriculture, artificial intelligence in agriculture and rural areas, and future enterprises and future regions. In addition to BMEL, the Federal Ministry of Education and Research (BMBF) also plays a crucial role in advancing agricultural digitalization. Details of these funding programmes can be found in Table 4. It is worth noting that the funded projects all emphasize sustainable and environmentally friendly agricultural practices, which align with the concept of regenerative agriculture.

Of the funded programmes listed in Table 4, only BMEL’s "Artificial Intelligence in Agriculture and Rural Areas" explicitly indicates its focus on integrating AI with agriculture. However, all other funding programmes are also related to AI to varying degrees. For example, four of the eight BMBF projects funded under "Agricultural Systems of the Future" concentrate on smart farming (BMBF, 2024). Notably, the projects "Digital Knowledge and Information System for Agriculture" (Digitales Wissens- und Informationssystem für die Landwirtschaft) and "Development of a Sustainable Cultivation System for Food in Resilient Metropolitan Regions" (Entwicklung eines nachhaltigen Kultivierungssystems für Nahrungsmittel resilienter Metropolregionen) have partnered with the Deutsches Forschungszentrum für Künstliche Intelligenz GmbH (DFKI) due to its expertise in AI technologies (BMBF, 2024). Additionally, BMEL’s programmes "Digital Experimentation Fields" and "Digital Intelligence in Agriculture and Rural Areas", which fall under the same funding framework as "Artificial Intelligence in Agriculture and Rural Areas", also support AI applications in agriculture, even though their names do not explicitly reflect this emphasis.

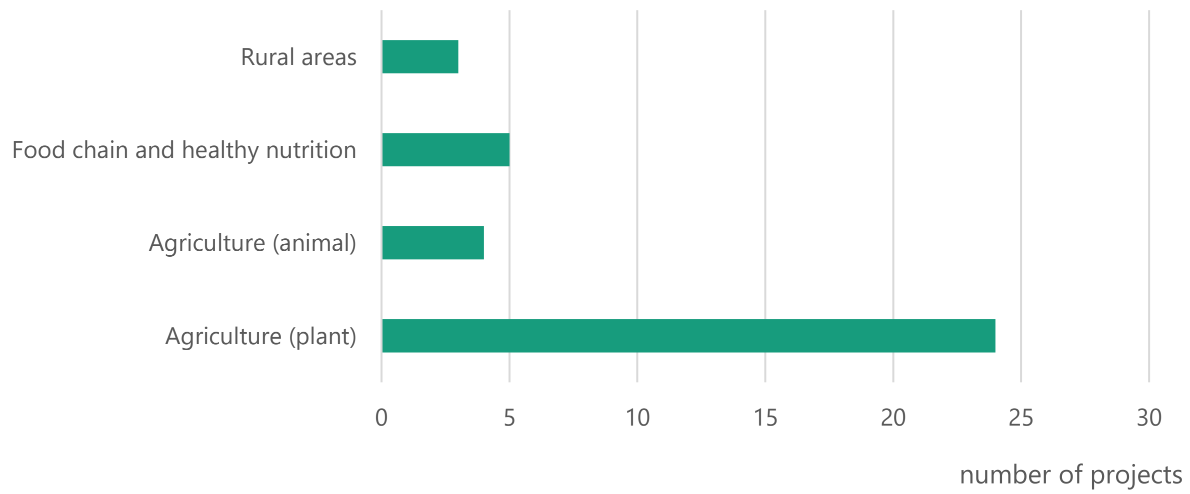
Table 4: Governmental funding for digitalization of agriculture in Germany

	Funding programme	Number of projects	Total budget (in million euros)	Funding source
1	Digital experimentation fields	14	70	BMEL
2	Competence networks			BMEL
3	Feasibility studies for government digital data platforms for agriculture	1	40	BMEL
4	Artificial intelligence in agriculture and rural areas	36	44	BMEL
5	Future enterprises and future regions	7		BMEL
6	Agricultural systems of the future	8	50	BMBF

Source: BMEL (2022a), BMEL (2024), BMBF (2020), BMBF (2024)

Under the "Artificial Intelligence in Agriculture and Rural Areas" funding programme, BMEL is supporting 36 joint research projects with a total grant amount of €44 million (BMEL, 2022b). These projects focus on six areas of AI defined by BMEL: Machine Learning, Deep Learning, Knowledge-Based Systems, Intelligent Machines (Robotics), Machine Planning and Action, and Pattern Recognition, Pattern Analysis, and Pattern Prediction (BMEL, 2022b). As shown in Figure 1, most of the funded projects address issues in agriculture, including both plant and animal production, such as plant breeding, plant health, weed control, livestock systems, and animal health. Fewer projects focus on using AI to enhance food safety and quality, improve transparency, promote sustainable and health-oriented consumer behaviour, and foster innovation in rural areas.

Figure 1: Topics of projects funded under the funding programme "Artificial Intelligence in Agriculture and Rural Areas" by BMEL



Source: BMEL (2024)

As mentioned in Section 2.2.1, obtaining data for training AI models poses a significant challenge if AI is to be adopted more widely in agriculture in the future. BMEL is aware of this challenge and has been providing broadband funding since 2008. As part of the Joint Task "Improving Agricultural

Structures and Coastal Protection" (GAK), BMEL has worked to enhance connectivity in underserved rural areas (BMEL, 2022b). Given the anticipated importance of 5G technology for data transfer between machines, BMEL has also ensured that agricultural requirements are considered in both the technical development and licensing processes (BMEL, 2022b). These efforts to improve data infrastructure are crucial for the anticipated large-scale applications of AI in regenerative agriculture.

So, to what extent is AI being employed in regenerative agriculture in Germany? There are no official statistics on the number of farms or the amount of land using AI technology in Germany. However, selected examples provide insight into the current capabilities of AI in German agriculture. According to BMEL, AI-based milking robots on many German farms now allow cows to decide when they want to be milked (BMEL, 2021). The Bosch-led Agri-Gaia project, funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK), utilizes AI for field route planning of agricultural machinery to save time and reduce fertilizer use (Bosch, 2022). In Rhineland, AI-based image recognition cameras are being installed on wine grape harvesters to ensure that only healthy grapes are collected for winemaking (DigiVine, 2024). In Lower Saxony, AI is being used to predict the timing of fungal infections in winter wheat, optimizing the dosage and timing of fungicides to improve their effectiveness (FarmerSpace, 2024).

2.3 Survey on impact and potential of artificial intelligence (AI) in regenerative agriculture in Germany

2.3.1 Methodology

The survey aimed to assess the impact and potential of Artificial Intelligence (AI) in regenerative agriculture in Germany. It targeted a diverse group of experts, primarily from ongoing or recently concluded research and development projects, including professionals in agricultural technology, crop science, environmental science, livestock management, ICT, and related fields.

Following a thorough review of the government-funded programmes listed in Table 4, we identified projects directly related to AI and regenerative agriculture and gathered information on their coordinators and/or contact persons. Notably, in most cases, the coordinator or contact person was a senior scientific researcher or consultant directly responsible for the project, rather than a manager.

In total, 120 senior researchers and consultants active in relevant R&D projects across Germany were selected to receive the questionnaire in December 2023 – January 2024. We received 20 responses, which, while a reasonable rate for this type of survey, represents a limited sample size, allowing only for descriptive analysis. As such, the survey should be considered exploratory, and the results interpreted with caution given the sample's size.

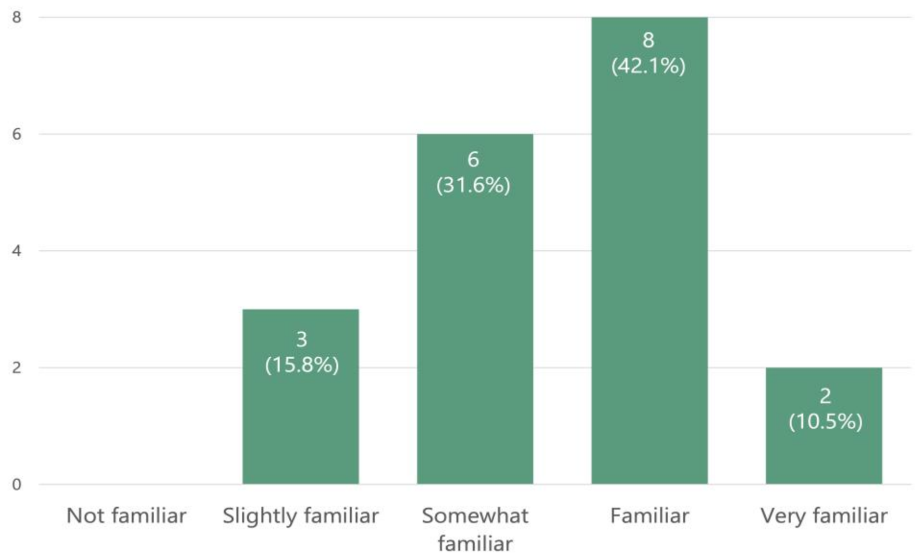
The survey explored several dimensions, including familiarity with AI technologies, the integration of AI into agricultural systems, and perceptions of AI's impact on sustainability goals like soil health, biodiversity, and carbon sequestration. Respondents also shared insights into financial and regulatory barriers to AI adoption in agriculture and identified potential areas for AI's future application.

The survey results provide a comprehensive overview of the current state and future prospects of AI in regenerative agriculture, highlighting both its potential and the challenges that must be addressed for successful integration into the agricultural sector.

2.3.2 Results

In evaluating respondents' familiarity with AI technologies used in agriculture, our survey revealed a generally moderate to high level of awareness among participants. The results in Figure 2 indicate that most respondents rated their familiarity positively. Specifically, eight respondents (42.1%) identified themselves as familiar with AI technologies, while six respondents (31.6%) indicated they were somewhat familiar. A smaller group of three respondents (15.8%) reported being slightly familiar, and two respondents (10.5%) indicated a very high level of familiarity. These findings suggest a broad spectrum of knowledge and understanding of AI technologies in agriculture. However, even among the respondents who are experts from funded projects we observe some lower familiarity ratings. It seems fair to assume that such lower familiarity is more widespread among potential users of AI in agriculture. Accordingly, there seems to be a need for targeted educational efforts to ensure a more consistent level of understanding and application of AI across the sector.

Figure 2: Survey question: how familiar are you with AI technologies used in agriculture? (19 Responses)



The analysis of survey responses regarding the integration of AI technology into regenerative agricultural systems shows the following distribution in Figure 3:

Mobile Technology is the most frequently cited, with 10 out of 11 respondents mentioning its use. This includes technologies such as drones and autonomous vehicles, indicating a notable presence of mobile AI solutions in agriculture.

Stationary Technology and Operational Software are each mentioned by 8 respondents. This category includes automated irrigation systems, sensor networks, and farm management software, reflecting a significant use of fixed-location and software-based AI applications.

Standalone Solutions, where AI operates independently without integration into other systems, are noted by 6 respondents. This suggests the use of specialized, task-specific AI applications.

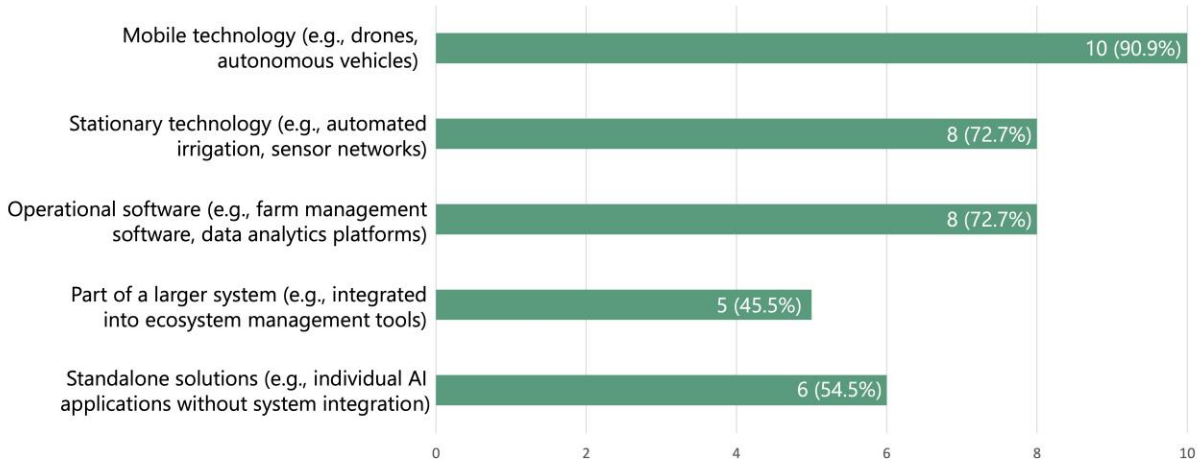
Part of a Larger System is acknowledged by 5 respondents, indicating that AI is utilized within broader ecosystem management tools, suggesting an understanding of AI as a component within a larger framework rather than as a standalone technology.

The distribution of responses indicates a diverse adoption of AI technologies in regenerative agriculture, with mobile technologies, stationary technologies, and operational software being the most prevalent[1]. This pattern corresponds to the varying maturity levels or application frequency of these

[1] The other two options were selected less frequently. While this could indicate that they are indeed less common applications of AI in regenerative agriculture, it is also possible that they were less clear to the survey participants.

technologies: mobile technologies like drones and automated machines incorporating AI are already in use for field production; stationary technologies, such as AI-enhanced sensor networks, are still gaining traction, partly due to their scale and cost; and operational software, including farm management platforms leveraging big data and large language models, holds significant promise, though its widespread implementation is still developing. As these technologies advance and become more ready for practical application, they are more likely to be recognized by experts.

Figure 3: Survey question: how is AI technology integrated into regenerative agricultural systems? select all that apply. (11 Responses)

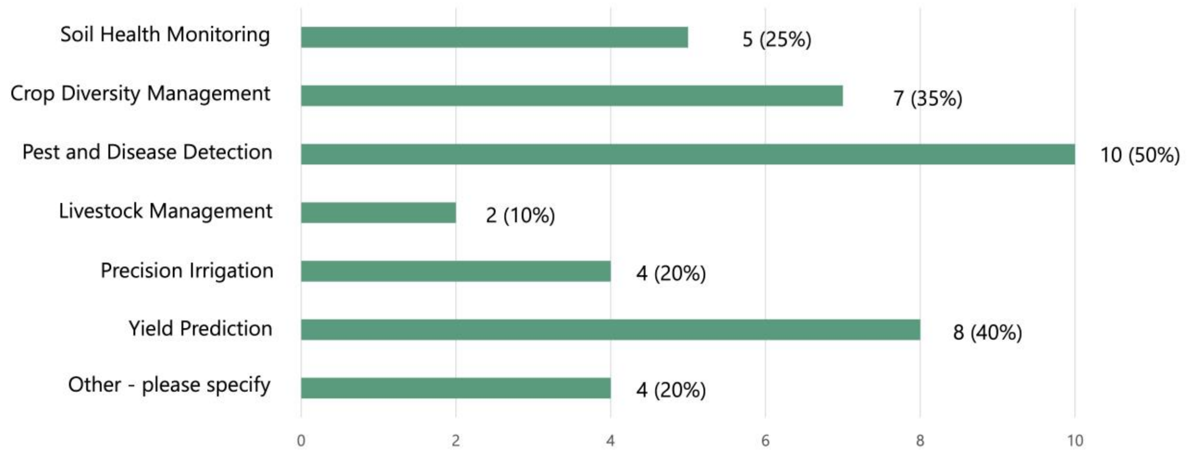


The survey responses regarding the AI applications currently used or known to be used in regenerative agriculture show a clear trend toward the preference for certain technologies in Figure 4. Pest and Disease Detection emerges as the most frequently cited application, with 10 mentions, underscoring its vital role in safeguarding crop health. Yield Prediction follows closely with 8 mentions, highlighting the critical importance of accurate forecasting in agricultural planning and resource management.

Crop Diversity Management, acknowledged by 7 respondents, reflects the emphasis on genetic variety for enhancing resilience and productivity. Soil Health Monitoring and Precision Irrigation, with 5 and 4 mentions respectively, further emphasize the sector's focus on maintaining soil quality and optimizing water usage for sustainability. Although less frequently mentioned, Livestock Management still features in the AI application landscape, as noted by 2 respondents. Other applications, grouped under "Other - please specify", received 4 mentions in total.

These insights reveal that the sector is increasingly utilizing AI to improve various aspects of regenerative agriculture – from crop health to logistical efficiency – with a notable emphasis on monitoring systems and predictive analytics.

Figure 4: Survey question: which of the following AI applications are you currently using or are aware of being used in regenerative agriculture? (20 responses)

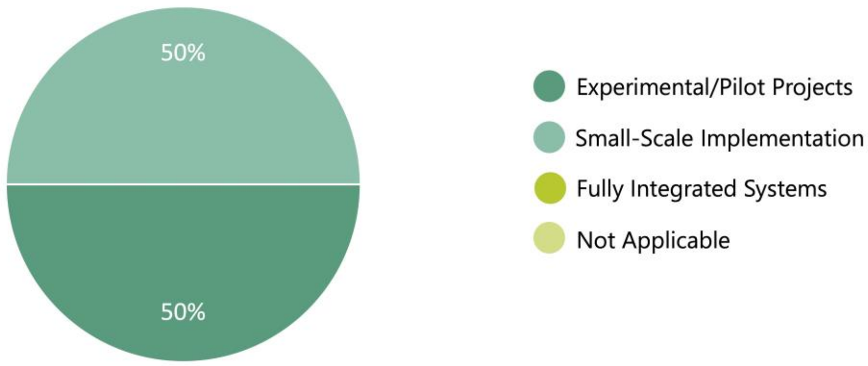


Other – please specify: Fence Management, Environmental Perception, Optical inspection of products in processing and packaging, Logistics in the value chain (for tracing products or environmentally relevant values of products)

In Figure 5, the responses regarding the scale of AI technology implementation in regenerative agriculture show an equal distribution between "Experimental/Pilot Projects" and "Small-Scale Implementation", each mentioned by 10 respondents. This balance indicates that while AI technologies are not only being actively tested in initial trials and experimental setups but are also beginning to be applied on a slightly broader, though still limited, scale.

This suggests that the sector is in a transitional phase, where stakeholders are both exploring and validating AI technologies while cautiously moving towards broader adoption. The equal split between these two implementation stages reflects a measured approach, with an emphasis on thoroughly understanding the technology's impact and effectiveness at smaller scales before committing full-scale integration.

Figure 5: Survey question: what is the scale of AI technology implementation you have observed in regenerative agriculture? (20 Responses)



In Figure 6, the survey responses regarding the main benefits of AI in regenerative agriculture practices show a strong consensus on "Increased Efficiency", with more than half of the participants citing it as the primary advantage. This highlights AI's potential to streamline operations and enhance the overall productivity of regenerative agricultural systems, even though efficiency is not a core goal of regenerative agriculture. "Better Disease Management" is the second most frequently mentioned benefit, acknowledged by a quarter of the respondents, reflecting AI's ability to facilitate early pest and disease detection, reducing the need for pesticides.

A few participants also noted "Enhanced Soil Health", underscoring AI's role in improving soil management and contributing to ecosystem sustainability. Additionally, one respondent mentioned "Cost Savings", pointing to the economic advantages AI can offer. Collectively, these insights emphasize AI's transformative impact on efficiency, plant health management, and soil conservation within regenerative agriculture.

Figure 6: Survey question: What are the main benefits of using AI in regenerative agriculture practices, in your opinion? (20 Responses)

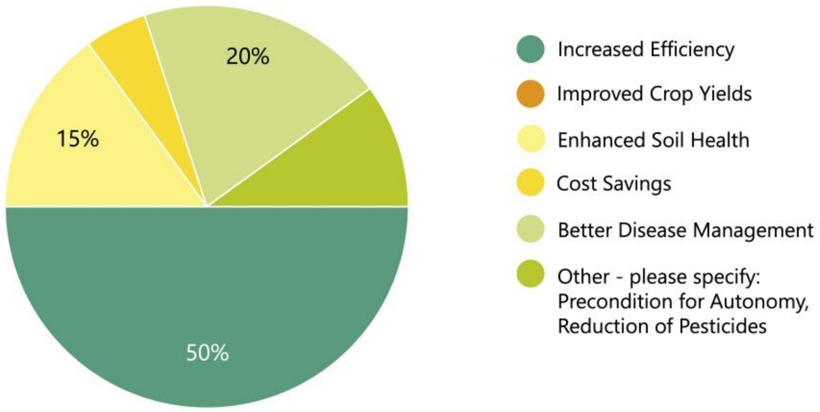


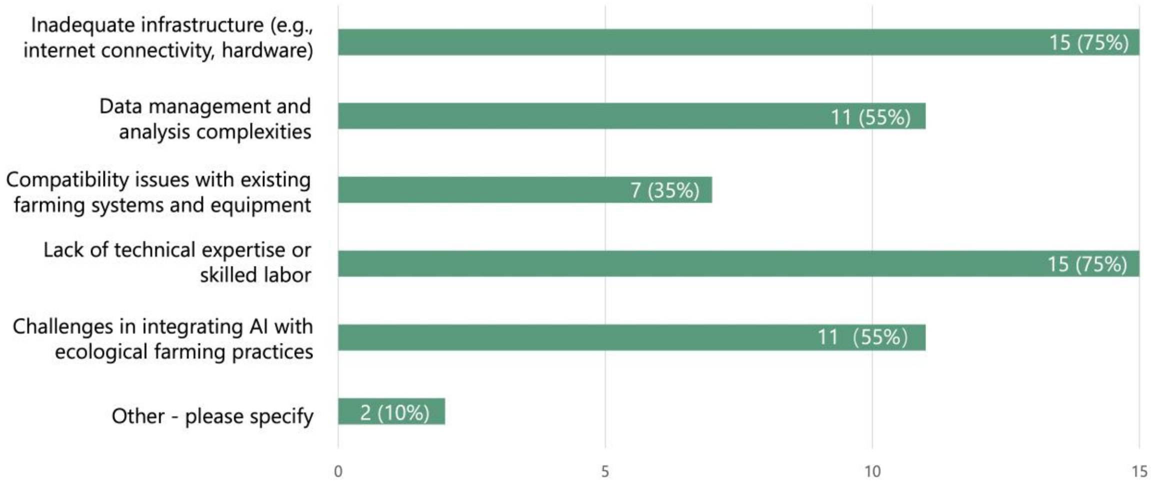
Figure 7 reveals that the most significant barriers to AI adoption in regenerative agriculture are "Inadequate infrastructure" and "Lack of technical expertise or skilled labour", each cited 15 times. These challenges highlight the urgent need for better infrastructure, such as reliable internet connectivity and advanced hardware, alongside a workforce skilled in implementing and managing AI technologies. This aligns with the challenges farmers face in adopting AI, as outlined in Section 2.2.1.

"Data management and analysis complexities" and "Challenges in integrating AI with ecological farming practices" were also frequently mentioned, with 11 respondents each identifying these as significant hurdles. Effectively processing the vast amounts of data generated by AI and aligning AI tools with sustainable farming practices requires sophisticated solutions that are not yet widely available. "Compatibility of AI with existing farming systems and equipment" was cited by 7 respondents, indicating the difficulties in aligning cutting-edge AI technologies with current agricultural tools and processes.

Other challenges, grouped under "Other - please specify", received 2 mentions, including cost-related concerns and interoperability. One respondent noted the "Cost of Adoption of new Technologies" as a challenge, however this may be less a technical challenge and investigated in the survey in an extra question.

These findings emphasize the diverse technical challenges facing AI adoption in regenerative agriculture. To overcome these obstacles, improvements in infrastructure, education, and system integration will be critical in facilitating broader AI implementation across the sector.

Figure 7: Survey question: what technical challenges do you think hinder the adoption of AI in regenerative agriculture? Select all that apply. (20 Responses)



Other - please specify: Cost of Adoption of new technologies,
Interoperability: especially semantical interoperability of concepts

Concerning the main barriers to the adoption of AI technologies in agriculture in Germany beyond technical issues Figure 8 indicates that "Uncertain return on investment" is the most pressing issue, mentioned by half of the respondents. This highlights a widespread apprehension about whether the financial investment in AI technologies will generate sufficient economic returns.

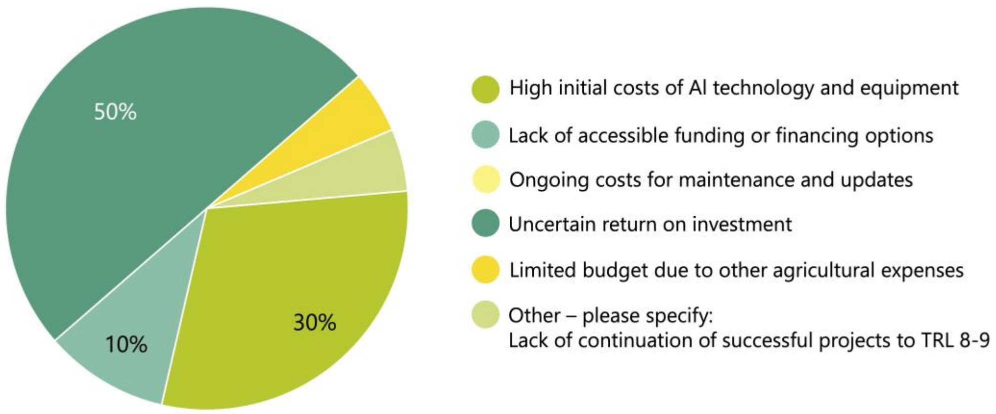
The "High initial costs of AI technology and equipment" were identified as a major hurdle by six respondents, pointing to the significant upfront expense involved in acquiring and deploying new AI solutions, which poses a considerable barrier for many farmers.

Additionally, "Lack of accessible funding or financing options" was noted by two participants, emphasizing the difficulty in securing the financial resources necessary to invest in AI technologies.

Other financial barriers, such as "Limited budget due to other agricultural expenses" and "Lack of continuation of successful projects to TRL 8-9", were each mentioned by one respondent. While these issues are recognized, they appear less prevalent compared to concerns about cost and return on investment.

These insights reveal that the financial challenges surrounding AI adoption in agriculture are multifaceted. The most significant obstacles include the uncertainty of economic benefits and the high initial costs, underscoring the need for clearer financial incentives and more accessible funding mechanisms to encourage wider AI implementation in the sector.

Figure 8: Survey question: what are the main barriers to the adoption of AI technologies in agriculture in Germany? Select all that apply. (20 Responses)



In Figure 9, the survey responses on regulatory and policy barriers to AI adoption in regenerative agriculture reveal several critical challenges. The most frequently cited issue is the "Lack of Guidance," indicating a strong need for clearer regulations and instructions on how AI technologies should be applied in agricultural contexts.

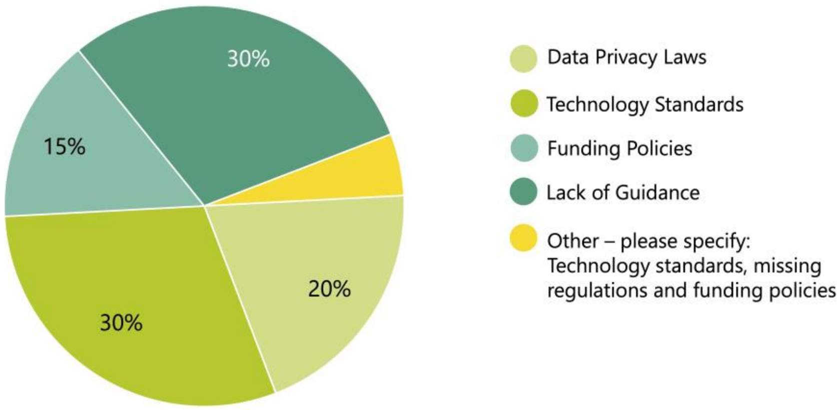
"Technology Standards" were also widely mentioned, highlighting the need for consistent technical guidelines to ensure seamless integration of AI into farming practices. "Data Privacy Laws" emerged as another significant concern, reflecting apprehension about how farm data is managed and protected under existing regulations.

"Funding Policies" were noted as an additional barrier by three respondents, suggesting that securing financial support for AI projects in agriculture remains challenging. However, considering that the German government has provided significant funding specifically for AI in agriculture, the issue mentioned in the survey may refer to difficulties in accessing these funding opportunities. Further information on the competitiveness of applying for these funds may be needed to fully understand this challenge.

One respondent pointed to a combination of "Technology standards, missing regulations, and funding policies", signalling broader systemic issues in the current regulatory framework supporting AI in agriculture.

Overall, these responses underscore the need for clearer guidelines, standardized technology frameworks, stronger data protection laws, and improved funding mechanisms to facilitate broader AI adoption in the agricultural sector.

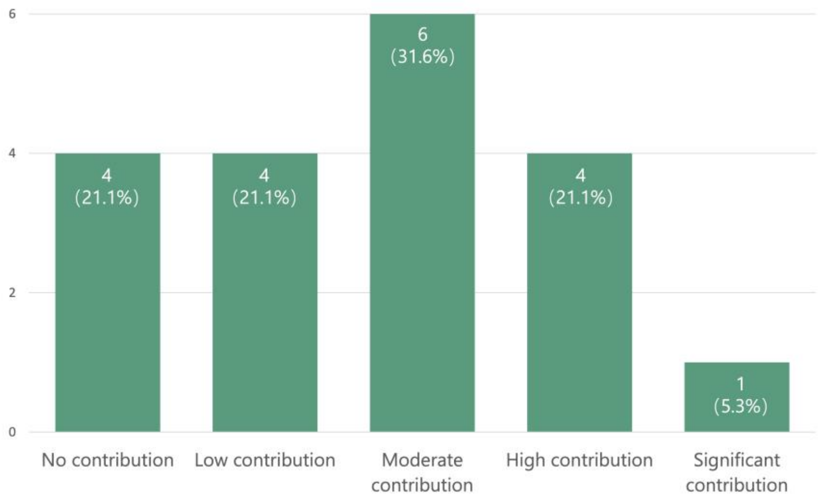
Figure 9: Survey question: what regulatory or policy barriers do you perceive in the adoption of AI in regenerative agriculture? (20 Responses)



Survey responses regarding AI's contribution to improving soil health, biodiversity, and carbon sequestration in agriculture reveal a mixed overall sentiment. In Figure 10, around a third of respondents indicate that AI has a moderate impact in these areas. Meanwhile, four of participants believe AI has either a low or high impact, reflecting varied perspectives on its influence. Another four respondents indicated that AI currently contributes little or no benefit to these areas, while only one respondent felt AI has a significant positive impact.

These diverse responses suggest that while AI's potential to enhance soil health, biodiversity, and carbon sequestration is recognised, opinions on its present effectiveness vary. This range of views underscores the evolving role of AI in agriculture and highlights the need for ongoing development and assessment of its contributions.

Figure 10: Survey question: on a scale, how would you rate the current contribution of AI to improving soil health, biodiversity, and carbon sequestration in agriculture? (19 Responses)



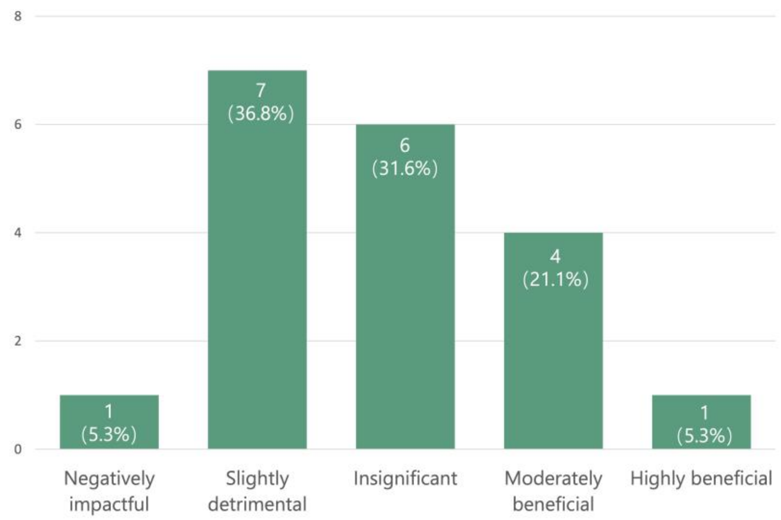
Survey responses regarding the current economic impact of AI in agriculture, including aspects such as cost savings and productivity improvements, reveal a range of perceptions in Figure 11. The most common perception is that AI has a slightly detrimental impact, as noted by 36.8% of respondents.

Many others, 31.6%, believe AI's economic impact is insignificant, indicating they do not see major benefits or harms at this time. A smaller group, 21.1%, view AI as moderately beneficial, reflecting a belief in more positive contributions to agriculture.

Interestingly, one respond each regard that AI's economic impact is either highly beneficial or negatively impactful, suggesting that opinions on AI's economic influence vary greatly among participants.

These responses highlight a mixed understanding of AI's economic contributions in agriculture. The varied perceptions underscore the complexity of AI's role in agricultural economics and suggest the need for further analysis and clearer communication regarding its potential benefits and limitations.

Figure 11: Survey question: how do you perceive the current economic impact of AI in agriculture (e.g., cost savings, productivity improvements)? (19 Responses)



Survey responses about the social impacts of AI in regenerative agriculture primarily highlight "Knowledge Transfer" and "Labor Dynamics Changes" as key areas affected, as shown in Figure 12. Many respondents emphasize "Knowledge Transfer", indicating that AI significantly aids in the dissemination and sharing of agricultural knowledge and skills. This underscores AI's role not only in enhancing farming practices but also in expanding the knowledge base of those involved in agriculture. At the same time, "Labor Dynamics Changes" were mentioned, signifying alterations in employment patterns and job roles within the sector due to AI adoption. These changes may include shifts in required skill sets, the creation of new job types, and possible reductions in certain manual labour roles because of increased automation. The potential impact of AI on the agricultural labour market, discussed in Section 2.2.1, is corroborated by experts with practical experience.

These responses reflect AI’s considerable social influence in agricultural, marked by advancements in knowledge sharing and notable shifts in labour dynamics, indicating a trend towards increased technological integration in the sector.

Figure 12: Survey question: can you describe any current social impacts resulting from the adoption of AI in agriculture? (19 Responses)

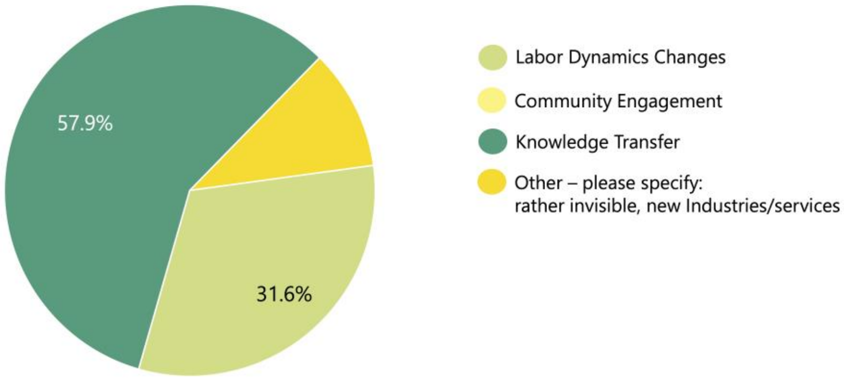
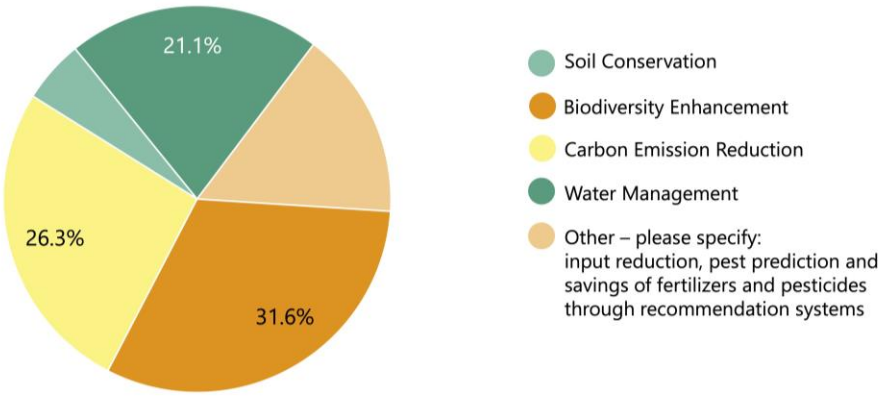


Figure 13 indicates that AI's most significant contributions to sustainability goals in regenerative agriculture are in "Biodiversity Enhancement" and "Carbon Emission Reduction." These areas are frequently mentioned, suggesting AI's role in promoting diverse ecosystems and reducing the environmental impact of farming practices. "Water Management" also emerges as another important area, reflecting AI's effectiveness in optimizing water usage. Other notable contributions include "Soil Conservation", emphasizing AI's role in maintaining soil health. Additionally, responses under "Other - please specify" highlight AI's impact on reducing input use, improving pest prediction, and enhancing the precision of fertilizer and pesticide applications to support sustainable agriculture.

Figure 13: Survey question: To which area do you think AI contributes the most to achieving sustainability goals in regenerative agriculture? (19 Responses)

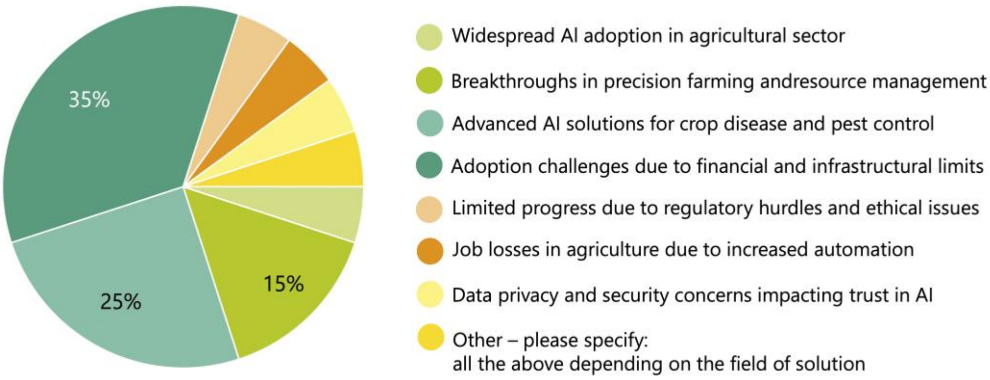


The survey on AI development in agriculture in Germany by 2030 reveals a nuanced outlook in Figure 14. Many respondents, who are experts in AI and agriculture, express optimism about AI's transformative potential, especially in crop disease and pest control. This suggests confidence in advanced AI solutions enhancing farming practices. However, concerns about adoption challenges – primarily financial and infrastructural limitations – underscore apprehensions about the readiness for widespread AI integration.

While there is anticipation of progress in precision farming and resource management, significant issues remain regarding data privacy, security, and trust in AI. Some respondents also express concerns about potential regulatory and ethical hurdles, as well as the risk of job losses due to increased automation.

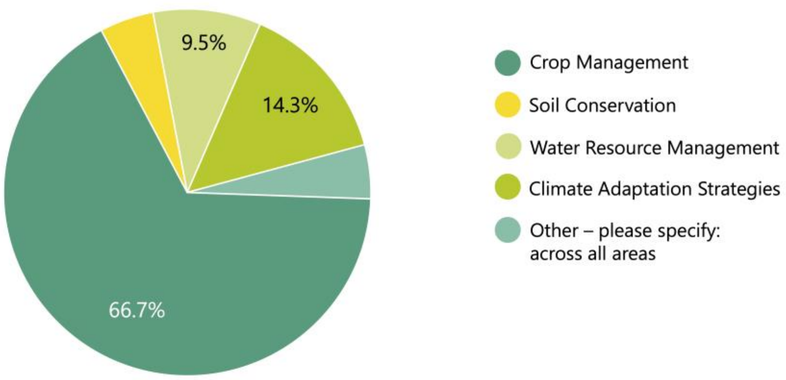
Overall, although there is optimism about the future benefits of AI in agriculture, it is tempered by concerns over financial, infrastructural, and regulatory barriers, along with the social impact of AI integration. This complex scenario highlights the necessity for well-balanced and carefully planned development strategies for AI in agriculture by 2030.

Figure 14: Survey question: what are your expectations for the development of AI in agriculture in Germany up to 2030? (20 Responses)



Survey responses on the potential applications of AI in regenerative agriculture by 2030 predominantly highlight "Crop Management" as the area with the most promise. As shown in Figure 15, many respondents repeatedly mention this area, suggesting a strong belief in AI's ability to enhance crop cultivation potentially through more efficient resource use, improved disease control, and optimized yields. "Climate Adaptation Strategies" and "Water Resource Management" are also recognized as key areas where AI could have a significant impact. These mentions reflect a growing awareness of the importance of adapting agricultural practices to changing climatic conditions and managing water resources more efficiently, both crucial aspects of sustainable agriculture.

Figure 15: Survey question: which areas do you see as having the most potential for AI application in the future of regenerative agriculture? (20 Responses)



Summary

An additional comment, not covered by any question in the survey, from an expert, raises concerns about farmers' reluctance to invest in new AI technologies. The expert notes that farmers may be sceptical due to fears of inadequate support for hardware or software, particularly from small startups. There is concern that invested technology might become obsolete, with spare parts becoming hard to obtain when urgently needed. Additionally, there is worry about the overselling of AI capabilities; if AI solutions are only 90% reliable, they may not meet the precision and dependability required for practical farming. The expert anticipates that major players will need to step in to drive the development of robust AI solutions.

Summing up, the survey provides, to our knowledge, the first expert-based assessment on the potential, current impacts, and barriers of AI in regenerative agriculture. However, it should be noted that only a limited number of respondents, mostly researchers from publicly funded projects, participated. Results from other surveys show that different stakeholder groups may view certain issues differently. Where data is comparable, the results appear consistent with those of other surveys, such as those on digitalization in agriculture. For instance, a recent study by the German Expert Group on Research and Innovation (EFI) found that farmers, who bear the investment costs of digital technologies, see these costs as a key barrier, especially in light of the prices for their final agricultural products (Geppert et al., 2024). This is in line with the notion of high initial costs for AI technology and equipment in this survey.

The survey could provide only limited insights regarding the impact of AI on sustainability. In the survey, half of the experts named efficiency as the most important impact, which could imply a higher environmental burden if the intensification and extension of agricultural practices outpace potential savings in resources. The study for the EFI derives similar conclusions and points out that the currently available digital technologies are primarily developed and used to optimize farming processes and increase crop yield for economic purposes. In contrast, the development and digital analysis of data related to nature conservation indicators is still in its early stages.

2.4 Conclusion

In conclusion, our study highlights both the potential and the challenges of integrating artificial intelligence (AI) into regenerative agriculture. The literature and also as result of our expert survey point out several interesting contributions of AI to regenerative agriculture are pointed out. However, practical implementation currently seems to be at a rather early stage and uncertain which foci of impacts (e.g. efficiency vs. broader sustainability considerations) will be chosen by the actors. While AI is already contributing to areas such as soil health monitoring, biodiversity tracking, and resource optimization, its application remains largely confined to small-scale or pilot projects. Moreover, there are key barriers to exploit the potential, including inadequate infrastructure, data management complexities, and the high costs associated with AI technology, all of which hinder broader adoption in regenerative practices. The results of our survey, reflecting expert opinions, align with our analysis of the challenges AI faces in regenerative agriculture in Section 2.2.1.

Moreover, our analysis indicates gaps between AI's current implementation in regenerative agriculture and its more established role in traditional farming. In traditional agriculture, AI is primarily applied to increase productivity and efficiency through automation, such as in harvesting and machinery maintenance. In contrast, while AI shows promise in regenerative agriculture, particularly in promoting environmental sustainability, its application is still in the early stages. Notably, a substantial portion of the AI applications and benefits cited by experts in the survey were aligned with traditional agricultural goals, such as improving yield and efficiency, with a notable focus also on regenerative practices like soil health and disease management. This highlights the need for further empirical research, as the literature on AI's long-term impact in regenerative systems remains sparse. While surveys are valuable in addressing this knowledge gap, especially given the absence of official data, our expert survey remains a second-best alternative to a user-focused survey, which was beyond the scope of our study.

In addition, it is important to acknowledge that, while our survey targeted experts with substantial experience and deep understanding of AI and agriculture, the overall number of participants was relatively small, despite a reasonable response rate. This limitation may introduce bias into the results and affect the generalizability of our findings. Moreover, for practical reasons the survey questions were limited and e.g. did not ask about specification of AI techniques being applied. In future research, there may be opportunities to conduct larger-scale surveys to capture a more diverse range of perspectives. In addition, qualitative approaches such as interviews or workshops with relevant stakeholders would be beneficial. Expanding the methodology and the participant pool to include experts from major companies involved in AI research and development, large-scale and small-scale farmers, as well as government representatives, could provide a more comprehensive understanding of AI's role in agriculture.

This broader approach would help refine our insights and offer more robust conclusions. Content-wise further research may investigate how AI effectively scale from improving efficiency to achieving broader environmental goals, such as soil carbon sequestration, biodiversity restoration, and resilience to climate change? From a policy perspective, future research may focus on how AI can be more comprehensively integrated to support regenerative goals while overcoming the technical, financial, and policy challenges currently impeding its widespread adoption. In addition, a stronger focus on the user perspective considering questions such as trust in and control of AI would be needed. Addressing these open questions will be essential to unlocking AI's full potential in driving both agricultural productivity and environmental sustainability.

3 Second-generation bio-based surfactants

Authors: Sven Wydra, Mengxi Wang

3.1 Introduction

3.1.1 Background

According to European CEN standards, a bio-based surfactant is "a surface-active compound that is wholly or partly derived from biomass produced either by chemical or biotechnological processing". Bio-based surfactants present a flagship product group and 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. A key recent development is the high focus of R&D&I activities on the so-called second-generation of bio-based surfactants, namely microbial bio-based surfactants (e.g., rhamnolipids, sophorolipids, surfactin). They are fermentation-based, produced by microbes – such as fungi, yeasts, and bacteria – through metabolic processes (Albrecht et al., 2022), hence also termed as microbial surfactants. In contrast, first-generation biosurfactants are generally chemically synthesized, often requiring refined substrates like carbohydrates, amino acids, oils, and fats (Albrecht et al., 2022). While both types are considered as bio-based surfactants, this report emphasizes the significance of second-generation biosurfactants. Second-generation biosurfactants are made from different feedstock, e.g., sugars but also from food waste, which are currently under development.[2] Usually, they do not use tropical oils such as many first-generation biosurfactants. 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).

The very recent opening of Evonik's second-generation biosurfactants facility in Slovakia may present the beginning of a strong dynamic development in this segment (Evonik, (2022). With its relatively limited resource need compared to other chemicals and innovativeness, this could be a segment in which German or other European locations play a strong role in the future.

3.1.2 Aim of the case study

This case study focuses on second-generation biosurfactants as a potential flagship for the future bio-chemical industry in Germany and Europe. It aims to clarify the position of Germany in international competition and to provide an in-depth analysis of the industry's dynamics, including its drivers and barriers. For the quantitative characterization of the industry, we elaborate a database for second-generation biosurfactants. In addition, an overview of potential economic and ecological impacts is provided.

3.2 Patents, industry and market development

In this chapter, a comprehensive exploration of the technological, industry, and market dynamics surrounding biosurfactants is undertaken. Firstly, attention is given to the realm of patents, where the allocation across different countries and regions is analysed to unveil key trends. Next, the focus

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

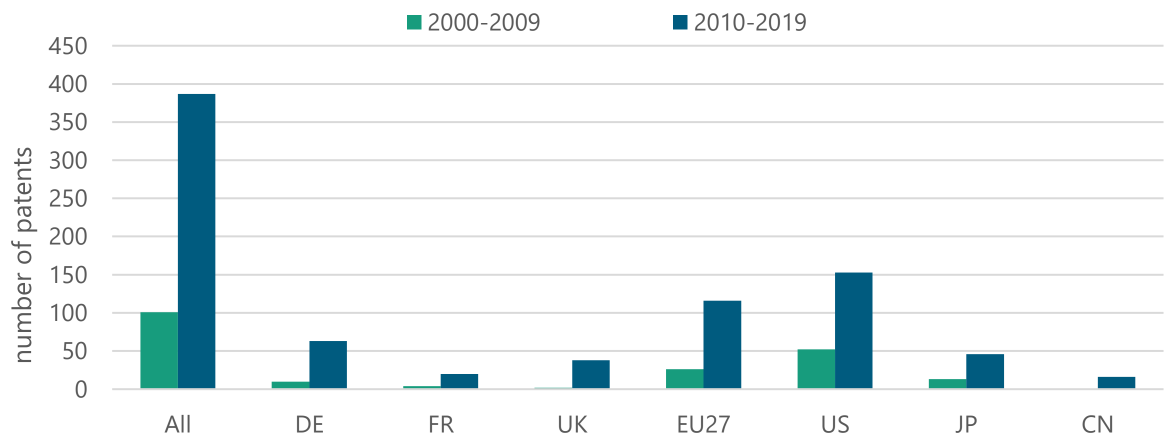
shifts to the biosurfactant industry, where the landscape of companies involved in biosurfactant-related activities, including their size, establishment year, and geographical distribution, is described. Finally, navigation through the market outlook occurs, uncovering the drivers and barriers shaping the biosurfactant market, such as market size, growth rates, and the types of commercialized biosurfactants currently dominating the market Through this systematic exploration, a systematic understanding of the multifaceted dynamics driving the biosurfactant landscape is provided.

3.2.1 Patents

We elaborated patent indicators to assess the global technological (patents) dynamics, as well as the current competitiveness and specialization of Germany in these areas. To identify relevant patents of second-generation biosurfactants we used a query based on a combination of keywords and biotechnology patent IPC-groups in the STN database.[3]

Figure 16 compares the number of patents related to second-generation biosurfactants in major countries and regions worldwide during the time periods 2000 to 2009 and 2010 to 2019. It is important to note that a patent can be jointly applied for by multiple companies. Therefore, the total number of patents cannot simply be considered as the sum of all patents across countries worldwide.

Figure 16: Transnational patents for second-generation biosurfactants, comparison of 2000-2009 and 2010-2019



Source: Fraunhofer ISI based on STN

It is evident that the total number of patents globally quadrupled in the 2010s compared to the 2000s. Among the largest economies in Europe, the US, and Asia, there is a significant increase. In Europe, Germany, France, and the United Kingdom experienced increases larger than the global average, especially the United Kingdom, where the number of patents on second-generation biosurfactants rose 19 times over the decade of the 2010s. The US had already been a leader in relevant patents in the 2000s; perhaps as a result, the increase in the 2010s was limited and lower than the global average, but its total number of patents still maintains a leading position globally. The EU27, as a whole lacks behind the US, but has a higher growth rate in the last decade. Lastly, Japan and China, as the largest Asian economies, are included in the observation. Japan started developing second-generation surfactant technology earlier and maintained steady growth in the 2010s in line with the global trend. Meanwhile, China has emerged from scratch as a new and active member in the global second-generation biosurfactant innovation field.

[3] The concrete query was (rhamnolipid* OR sophorolipid* OR sophorolipid* OR surfactin* OR bio-surfactan* OR biosurfactan*) OR (surfactant* AND C12/IPC,CPC)

3.2.2 Bio-based surfactants industry

3.2.2.1 Data sample

For bio-based surfactants, no publicly available industry data exists yet. In order to analyse the company landscape, we compiled our own company database by utilizing company data from Crunchbase[4] to identify relevant companies. As a leading worldwide provider of company data, Crunchbase covers a wide spectrum of businesses, from early-stage startups to the Fortune 1000. Typically, Crunchbase's company data includes information such as a company's description, location, founding date, funding details, team composition, and events.

To identify firms, we implemented a three-step approach:

First, we searched for companies via keyword research for biosurfactants, and from the more detailed descriptions, we identified firms either cooperating with biotechnology firms or utilizing bio-based resources beyond traditional oils, etc. We consider this as a proxy to identify second-generation bio-based surfactants companies. By this keyword approach a few "traditional" bio-based surfactants company working with rather well-established processes could be included. However, for most of them, there are clear indications of innovative activities towards second-generation biosurfactants. Therefore, we refer to the term "second-generation biosurfactants" in the following.

Second, through the patent analysis described above, we identified the top 100 companies in patenting, and those companies not yet identified from Crunchbase in step one were added to our database. In many cases, multiple companies belong to the same holding or were already identified in step one; therefore, only a limited number was added.

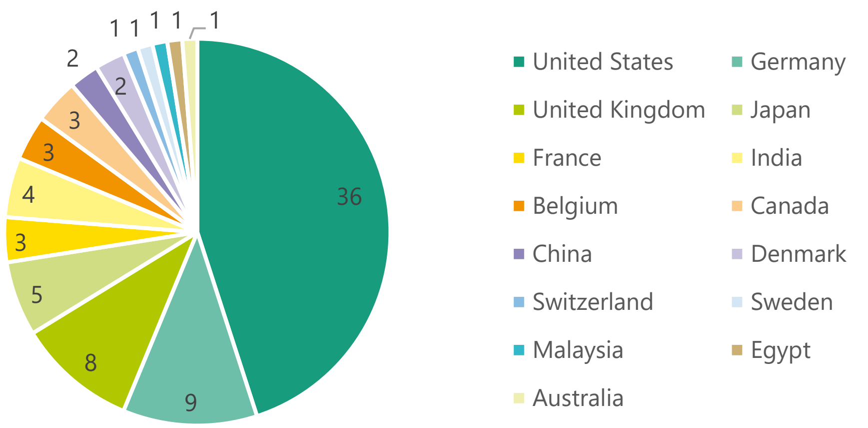
As a control step, the outline of firm presentation in market studies dedicated to microbial surfactants were used, but no additional entries were identified.

3.2.2.2 Status-quo and trends of second-generation biosurfactants

In total, we identified 81 companies that are engaged in the development, manufacturing, or distribution of second-generation biosurfactants. Illustrated in Figure 17, these companies are headquartered across 15 countries, with approximately 45% situated in the United States, followed by Germany and the United Kingdom. Regionally, North America emerges as the dominant force in this industry, hosting around 50% of second-generation biosurfactant-related companies, with the United States leading in terms of the number of companies. Europe holds the second-largest position, contributing roughly 35% to the global second-generation biosurfactant landscape, distributed among seven European countries. Asia follows closely with 15% of the total companies, primarily represented by Japan and India. Moreover, companies from Africa and Oceania participate in the industry, albeit to a limited extent.

[4] www.crunchbase.com

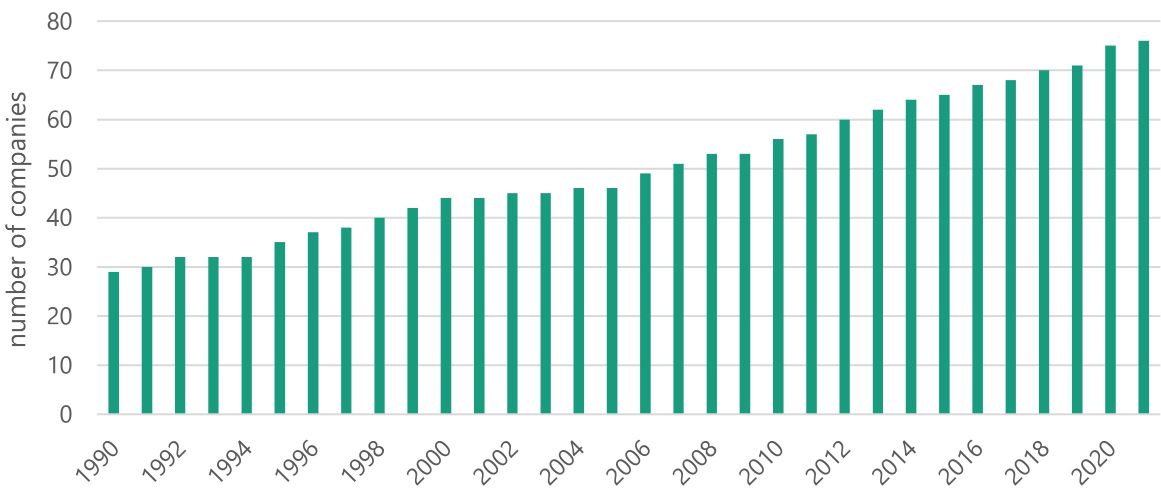
Figure 17: Global distribution of second-generation biosurfactant companies



Source: Fraunhofer ISI based on Crunchbase

Figure 18 visually depicts the development of companies currently operating in the biosurfactant business since 1990. Since the founding year of four biosurfactant-related companies is unknown, this figure only reflects the founding year of 77 companies. It is worth noting that, although the technology of biosurfactants started to grow rapidly after 2000, at least half of these companies developing and manufacturing biosurfactants were established before 2000. This includes most of the large companies with more than 10,000 employees, many of which had extensive prior experience in traditional chemical production before venturing into biosurfactant research and development. Between 2000 and 2006, the count of companies presently providing biosurfactants remained stable. However, since 2006, the number of these companies has once again started to rise steadily. Most of the companies established in this period are biotechnology-based and offer biosurfactants as one of their main products. This development reflects the two primary patterns of companies currently offering biosurfactants: those rooted in the traditional chemical industry moving towards a more sustainable future, and those that have specialized in modern biotechnology since their establishment.

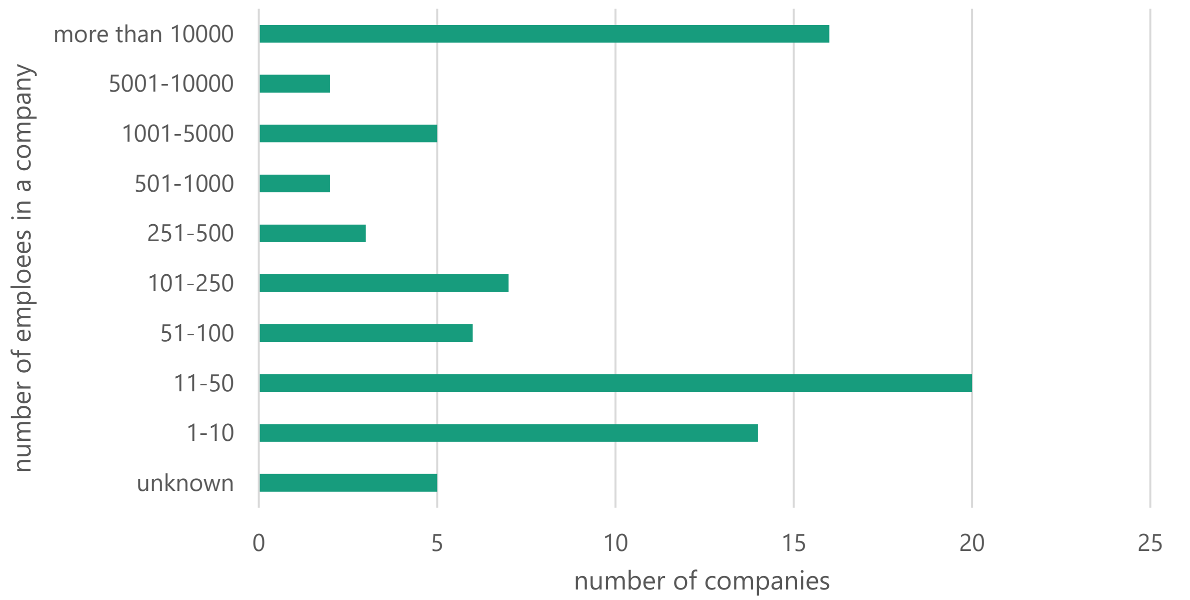
Figure 18: Development of biosurfactant companies since 1990



Source: Fraunhofer ISI based on Crunchbase

Figure 19 provides an overview of the size of companies within the biosurfactant industry. Apart from five companies with an unknown number of employees, approximately half of the companies have fewer than 100 employees, while about a quarter fall within the range of 100 to 10,000 employees. In specific, one-fifth of the companies have more than 10,000 employees. In addition, companies with 11 to 50 employees are the most prevalent in this industry, totalling twenty such companies. The second most common company size consists of those with over 10,000 employees, followed by micro-companies with 10 or fewer employees. In conclusion, the biosurfactant industry is characterized by a majority of companies that are either of substantial size or notably small, based on the number of employees.

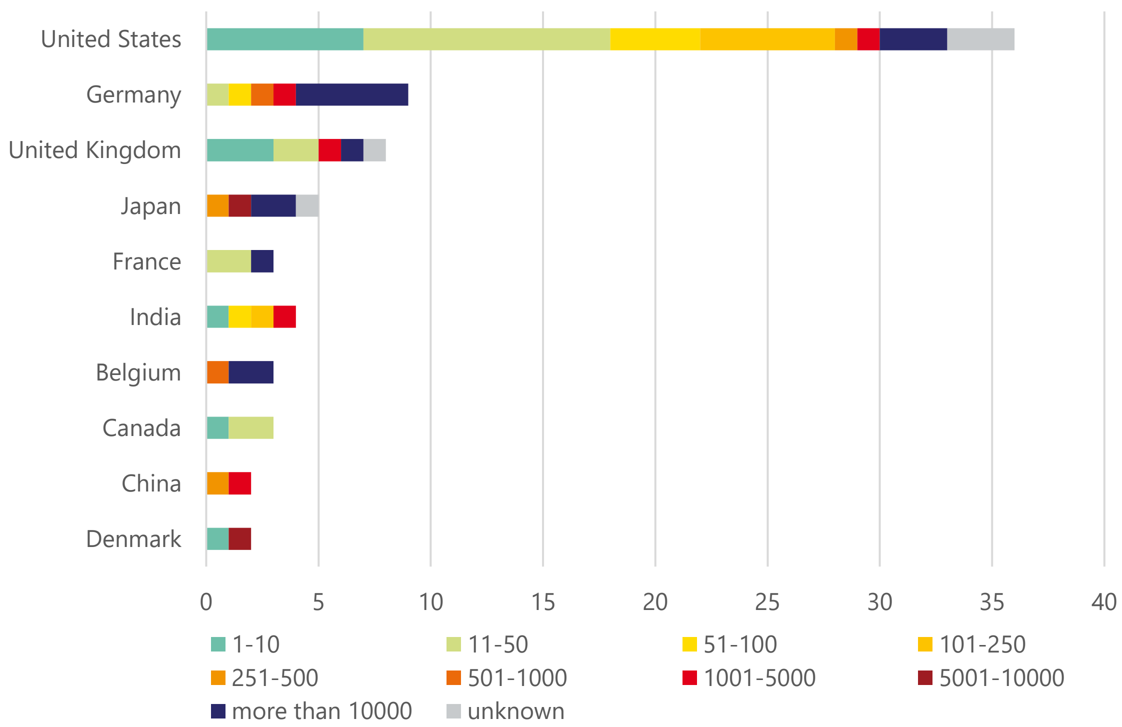
Figure 19: Size distribution of companies in the biosurfactant industry



Source: Fraunhofer ISI based on Crunchbase

Figure 20 portrays how companies are sized in the top ten countries with the most companies providing biosurfactants. On the one hand, most small companies with fewer than 100 employees are located in North America, either in the United States or Canada. Similarly, the majority of biosurfactant-related companies headquartered in the United Kingdom are also small companies. On the other hand, large companies with more than 10,000 employees are mainly situated in the European region, most notably in Germany. Outside of Europe, these types of large companies exist only in Japan and the United States. Specifically, the United States, as the preferred country for the headquarters of most biosurfactant-related companies globally, is home to companies of all sizes, small, medium, and large ones. Additionally, it's worth noting that among the ten countries with the most biosurfactant-related companies, there are no small companies involved in biosurfactant R&D and production in Japan, Belgium, and China.

Figure 20: Company size distribution in Top 10 biosurfactant-producing countries



Source: Fraunhofer ISI based on Crunchbase

3.2.3 Market

In the last few decades, with advancements in biochemical technology, the first generation of biosurfactants has seen significant development. Conversely, the development of second-generation biosurfactants has primarily occurred in the last two decades (Kleinen, 2023). The global surfactants market reached approximately US$35 billion, with bio-based surfactants accounting for around 4% (US$1.4 billion) (Albrecht et al., 2022; Schonhoff et al., 2023). Despite this modest market share, the global bio-based surfactants market is expected to undergo substantial growth alongside the overall surfactants market. Forecasts differ in the projected growth, and a set of market studies indicates a market volume in the range of US$1.7 to US$3.1 billion until 2030[5]. This growth is attributed not only to the increased demand for hygiene and sanitation products during and post-COVID-19 pandemic (Miao et al., 2024) but also to consumer preferences for sustainable products and regulatory authorities' focus on sustainability goals (Begum et al., 2023; Miao et al., 2024).

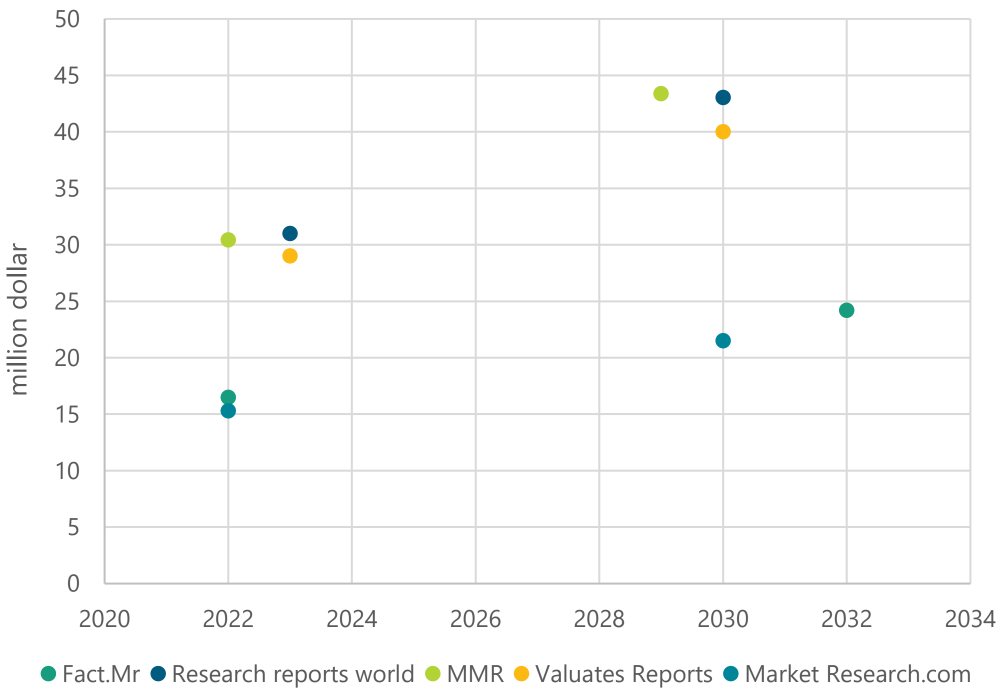
The market for second-generation biosurfactants is usually covered with the term microbial biosurfactants. The estimations of some current studies are presented in Figure 21[6]. These studies estimate the current market size to around US$15 to US$30 million, which would imply a share of microbial surfactants of the total market (US$35 billion) of less than 0.1% (Schonhoff et al. 2023).

[5] https://www.marketsandmarkets.com/Market-Reports/biosurfactant-market-163644922.html; https://reports.valuates.com/market-reports/QYRE-Auto-12W12230/global-biosurfactants; https://www.zionmarketresearch.com/report/biosurfactants-market ; accessed on 23.11.2024

[6] In addition, there are very few market studies that claim that the current microbial surfactants market would be 5 times or even 100 times higher, as there are no indications for such differences, those outliers are not considered here further. Please see https://medium.com/@mariad13206/microbial-surfactant-market-size-growth-forecast-2023-2030-4435035dde4a or https://www.verifiedmarketreports.com/product/microbial-biosurfactants-sales-market-size-and-forecast/

Moreover, with an expected annual growth rate of around 4-5% for the next year, we anticipate that the diffusion of microbial surfactants and the potential substitution of fossil-based or oil-based surfactants will not occur rapidly.

Figure 21: Market estimates for microbial biosurfactants



Source: Estimates from different market studies - Fact.Mr (2023), Research reports world (2023), MMR (2023), Valuates Reports (2023), MarketResearch.com (2023)

Commercialized second-generation biosurfactants include sophorolipids (SLs), rhamnolipids (RLs), mannosyl erythritol lipids (MELs), lipopeptides (LPs), phospholipids/fatty acids, as well as particulate and polymeric biosurfactants (Albrecht et al., 2022). Among these, SLs claim the largest market share, trailed by RLs and MELs (Albrecht et al., 2022; Schonhoff et al., 2023), all falling under the glycolipid category. This ranking mirrors the application breadth and production process maturity of these second-generation biosurfactants. For example, Evonik, a prominent provider of second-generation biosurfactants, has developed commercial-scale manufacturing platforms for SLs and RLs but not for MELs, as disclosed in 2021 (Evonik Personal Care, 2021). In detail, SLs find extensive applications across various sectors, including household detergents, agriculture, food, and the pharmaceutical industry (Albrecht et al., 2022). The substantial market share of RLs is attributed to high demand from diverse end-use industries, particularly cosmetics and personal care (Fortune Business Insights, 2022). It is important to note that RLs and SLs have different properties and HLB[7] values, therefore they are not interchangeable in a given application[8].

The European market serves as a pivotal revenue driver for microbial biosurfactants worldwide, wherein their "demand is driven by extensive usage in cosmetics" and detergents (Schonhoff et al. 2023). This dominance is intricately intertwined with the vibrant landscape of research and development, as well as the vigorous commercialization efforts unfolding within Europe.

[7] hydrophilic–lipophilic balance

[8] The HLB value can be used to predict the surfactant properties of a molecule and can be used to classify the surfactant function

Players in the European, particularly German, chemical sector play indispensable roles in this ecosystem. For instance, SLs are meticulously developed and industrially produced by B2B enterprises such as Evonik, subsequently finding applications in household detergents and personal care products by B2C giants like Henkel and Ecover. Similarly, in the case of RLs, the collaborative efforts of Evonik and Unilever led to the introduction of RLs as a revolutionary sustainable foaming agent in hand dishwashing liquid under the brand name Quix in 2019, marking a significant achievement (Unilever, 2022). The success of this endeavour prompted Unilever's plans for global expansion of RLs into other product lines, thus catalysing the establishment of Evonik's pioneering industrial-scale plant in Slovakia for RLs manufacturing (see box below).

Other emerging European companies include AmphiStar, a spin-off of the Bio Base Europe Pilot Plant. It claims the distinction of being the first company to develop, scale-up, produce, and market sophorolipid biosurfactants sourced entirely from bio-based waste and by-products (AmphiStar, 2023; Bio Base Europe Pilot Plant, 2023). It had its first commercial launch in May 2023 with a multi-surface cleaning product for eco-cleaning brand Ecover which is 97% food waste-derived (Lim & Langham, 2023).

The following table summarizes some current investments in RLs.

Table 5: Current investment in industrial-scale facilities for RLs

	Volume	Opening date	Location	Source:
Evonik	> 10 kta (estimation)	2024	Slovakia	Lim & Langham (2023)
Locus Fermentation Solutions	2,5 kta	2023	US	Locus Fermentation Solutions (2023)
Hoilferm	15 kta	3,5kta until 2024, 15kta later	UK	Bettenhausen (2024)
Stepan	20 kta	n.a.	US	Bettenhausen (2022)

Source: see sources in table

The most significant **driver** in the development of second-generation biosurfactant technologies and markets is the concept of sustainability (see also Section 3.3.1). On one hand, the better long-term availability and sustainability of renewable bio-based raw materials compared to fossil-based ones, coupled with the fact that second-generation biosurfactant technology does not require the use of refined substrates and significant energy inputs (Albrecht et al., 2022; The American Cleaning Institute, 2022), have motivated manufacturers to intensify research and development efforts in this area on the supply side of the market. On the other hand, at least some synthetic surfactants pose certain environmental risks and safety concerns, including toxicity, partly poor biodegradability, and eutrophication effects. Moreover, in the market of personal care second-generation biosurfactants are considered competitive as "...the market segment is characterized by (1) a higher accepted average cost of the used surfactants and (2) a clear continual pressure from consumers based on "green" factors, climate change, carbon footprint, avoidance of animal fats, deforestation linked to palm oil, but also mildness and undesired activities linked with preservatives in such products" (Roelants & Soetaert, 2022, p.13). Also, unique performance regarding foaming properties is potentially relevant for some applications. In addition, several uncertainties on both the supply and demand sides contribute to the market share growth of second-generation biosurfactants. For instance, the COVID-19 pandemic has reshaped public focus towards hygienic cleaning products, which represent the most prominent use of surfactants.

However, it has to be noted that not all potential advantages are relevant for a certain application or that no other surfactant is able to meet some of these. For example, according to the EU Regulation (EC) No 648/2004 (detergency regulation), all detergents must be 100% biodegradable. Therefore, biodegradability of RLs or SLs is not a unique selling proposition; other surfactants used also fulfil this criterion.

The most significant **challenge** to the commercialization of biosurfactants today is the high production cost and hence prices. While prices and costs are only partially disclosed, it is estimated roughly that production costs for microbial biosurfactants are three to ten times higher than that of fossil-based surfactants (Begum et al., 2023; Roelants & Soatert, 2022; Noll et al., 2024). Research by Schonhoff et al. (2023) shows a significantly larger variety of prices, whereby the exemplary data for RL (38 sources) shows a range which differs by a factor of up to 2000. A main reason for this high variety is that the purity, type, physical state, or purchase quantities differ.

Low yields and high feedstock prices are the main reasons for these high production costs. On one hand, the process of second-generation biosurfactants is not yet mature enough, and there is still much room for improvement in microbial species selection and cultivation, microbial genetic modification, and optimization of culture conditions (Miao et al., 2024). On the other hand, the cost of the substrate accounts for about 10-30% of the overall production cost, and even up to 50% in some cases (Mohanty et al., 2021; Miao et al., 2024). In addition, limited efficiency because of scale and investment costs for new installations required increase production cost (Roelants & Soetaert, 2022).

The strategy currently under consideration by academia and industry to significantly reduce production costs is to use waste as a substrate for culturing microorganisms. This approach not only addresses the expense of waste disposal and facilitates the utilization of waste streams but also enables profitability from waste and fundamentally lowers the cost of biosurfactant production (Begum et al., 2023; Mohanty et al., 2021). Recent studies have demonstrated that various substrates such as vegetable oil wastes, vegetable wastes, fruit wastes, starch wastes, etc., show promise as carbohydrate sources for biosurfactant production (Begum et al., 2023). However, the utilization of such feedstocks in industrial settings remains limited due to the heterogeneous composition of these feedstocks (Miao et al., 2024). An even more profitable solution would be the offset of waste disposal costs when waste is used as a fermentation substrate. Integrating waste treatment with biosurfactant fermentation, such as through integrated wastewater biorefineries, is likely to enhance the commercialization and profitability of biosurfactants. De Oliveira Schmidt et al. (2022) confirmed the viability of producing biosurfactants from cassava wastewater. As biosurfactant fermentation technology matures, more similar industrial chains may emerge in the future.

While there is potential to reduce costs across various aspects, it's unlikely that the production costs of biosurfactants will experience significant decreases in the near future.

Last, partly influenced by the higher costs of biosurfactants, the types, range of applications, and number of suppliers are still comparatively limited compared to traditional surfactants. While a wide range of different chemical surfactants can be combined in specific formulations to achieve the desired final product, it is not straightforward to make subtle changes to the structure of biosurfactants, as physicochemical or biological characteristics may change. Additionally, many products, such as those in personal care, are composed of many ingredients, requiring significant time and resources for reformulation with new ingredients. Consequently, for B2B suppliers, persuading customers to switch or explore new applications can be challenging (see box for Evonik).

Box: Evonik's investment in RL

After launching a few commercial RLs on a smaller scale, Evonik built the first industrial-scale plant for 2nd biosurfactants and opened it in early 2024 (Evonik, 2024). In detail, Evonik invested a "low three-digit million-euro sum" in the construction of this new production plant for bio-based and fully biodegradable RLs, with an estimated capacity of double-digit metric kilotons of RLs per year (Lim & Langham, 2023). The investment was made at an existing Evonik plant in Slovakia.

RLs are produced by fermenting sugar and aim to substitute products derived from fossil fuel or tropical oil. Therefore, the basis is still food biomass. Application areas currently prioritized in industrial D&I activities include personal care products (such as toothpaste with RLs already available in brands like Vademecum), various cleaning applications in home care (e.g., hand dishwashing liquid already available on the market), with others in the development stages. Additionally, industrial cleaning applications are also being planned. An important cornerstone is Evonik's long-term collaboration with Unilever for the commercial manufacturing and supply of Evonik's RLs for use in a range of Unilever's household cleaning products.

Evonik claims several environmental advantages of their RL surfactants compared to traditional biosurfactants derived from fossil fuels or oils:

- They are fully biodegradable[9].
- They exhibit low aquatic toxicity.
- They offer unique performance regarding foaming properties.
- The fermentative process requires less energy compared to traditional chemistry.
- They reduce the needs of polymers, builders, and stabilizers, and do not require solvents in the formulation. This results in less energy consumption related to transporting raw materials to the formulator's plant and contributes to a reduction in carbon footprint.
- Compared to current best-performing green laundry detergents, the Evonik formulation cleans better at half of the surfactant load[10].

However, the introduction of such a new biosurfactant on a commercial scale also poses challenges. RLs have different properties and HLB[11] values than other biosurfactants, making them not interchangeable in a given application. Moreover, a main challenge in this B2B market for Evonik and potentially others is to support and persuade the downstream industry to develop new applications that utilize the potentially superior characteristics of these new bio-based surfactants. While the prices of Evonik RLs are not disclosed, it is very likely that higher costs pose another market challenge.

3.3 Impact of second-generation bio-based surfactants

3.3.1 Economic impacts

In the EU, surfactants present only around 2% of the overall chemical production, and only a fraction of that is already bio-based.). Hence, any impact of bio-based surfactants discussed below is limited in magnitude as the additional volume of bio-based surfactants is low. Nevertheless, bio-based surfactants may have implications for the bioeconomy as a whole, not only directly, but also via

9 As noted above, also some other surfactants are fully biodegradable, so this is not a unique characteristic

10 https://www.cleaninginstitute.org/industry-priorities/sustainability/reporting-our-progress/rising-15degc-challenge-evonik-producing

11 The HLB value can be used to predict the surfactant properties of a molecule and can be used to classify the surfactant function

signalling and spillover effects to the broader (bio-) economy (see below). In the following, we discuss several economic impact pathways.

As explained above, second-generation biosurfactants' **prices** are and most likely will remain significantly higher than other tropical oil- or fossil-based surfactants. This will either hinder market growth or impose additional expenses of consumers, potentially leading to reduced spending elsewhere. However, this price effect is limited, as the surfactants account for only a fraction of the total product price. For instance, liquid dishwashing detergent, which typically retails at €3-5 per litre in Europe, contains up to 30% surfactants (Evonik, 2021). Accordingly, it could be expected that the inhibitory effect of higher prices for biosurfactants would be rather low.

Economically, bio-based surfactants present a rather **high value-added market**, although price competition is rather high and commodities are close to mass production. The use of innovative technology and prospectively alternative feedstock resources together with strong application sectors presents favourable conditions to secure Germany's **strong competitiveness.** In Germany, mostly larger players are active in microbial surfactants, while only a few smaller companies could be identified. This makes estimating the economic relevance rather impossible, as for the larger firms, the share of those activities of the total revenues and jobs cannot be estimated. Moreover, as the case of Evonik shows, the activities are geographically distributed across countries. Still, the current situation, where production facilities for second-generation biosurfactants are built up rather nearby the companies' headquarters, indicate at least potential for western countries' locations to stay attractive in this segment. Hence, the potential market uptake of microbial biosurfactants may present an opportunity to reduce the dependency on imports, which is currently high, as, for example, around two-thirds of the feedstocks used for EU production of bio-based surfactants are imported from non-EU countries (Spekreijse et al., 2019). Thus, microbial biosurfactants could also contribute to improving Europe's and Germany's technological sovereignty in this market segment.

In addition, while second-generation biosurfactants still face challenges, they present an interesting segment with high innovativeness and potentially less use of non-sustainable feedstock (fossil or tropical oil). If biosurfactants succeed to achieve considerable volume including a certain price premium, this could have **signalling effects** and transferable lessons in market and technical issues to other markets of the chemical industry for bio-based products. Hence, at least the potential for economic spillover effects is high.

3.3.2 Ecological contribution

Considering ecological effects, many authors claim a general ecological advantage of bio-based surfactants due to the use of natural resources, their low ecotoxicity, and high biodegradability. Moreover, potential advantages also derive from lower energy requirements for fermentation which are carried out under mild conditions at ambient temperature and pressure. This may lead to lower CO_2 emissions.

However, Briem et al. (2022) point out that "...they are not standalone indicators for sustainable products, but rather input parameters for a comprehensive sustainability assessment". Today, there is only limited holistic information available on the environmental performance of bio-based surfactants. For example, in a meta-study on bio-based surfactants Briem et al. (2022) found only six reliable LCAs, including only three reliable LCAs referring to microbial bio-based surfactants. Very recently, a few additional assessments have been published (Table 6), but with very specific foci regarding the boundaries, product, or scenario of comparison. In addition, most of the current assessment are based on lab-scale or experimental data, while data for scaled-up processes is still missing (Roetarts & Soatert, 2022; Briem et al., 2022). Besides methodological aspects of the life cycle assessment, the development stages and production scales of microbial surfactants differ strongly from the production of conventional surfactants and, therefore, offer limited comparability (Briem et al., 2022).

In the following, we summarize the results of the available studies, which contain the ones included in Briem et al. (2022), but also some more recent ones (Table 6). This overview illustrates that the different studies emphasize certain drivers of impact, and there are hardly comparisons to traditional fossil-based surfactants.

The following table aims to summarize the key foci and main results.

Table 6: Summary of LCA results for second-generation biosurfactants

Author	Investigated product and comparisons	System boundaries	Key result
Baccile et al. (2016)	application of SLs in a household hand-washing detergent at "larger scale" compared to reference products (fossil-based surfactants)	cra4dle-to-grave	total environmental impacts of the investigated SLs are in **the same range** as for the reference products environmental impacts of 2nd generation biosurfactants depend largely **on the raw material input**; optimization of the substrate ratio or the use of second-generation raw materials (e.g. non-food feedstocks) could lead to significant improvements
Kopsahelis et al. (2018)	rhamnolipids and sophorolipid in pilot production in Greece (reference year 2013)	gate-to-gate	**Environmental impacts of RLs** production are lower compared to those of **the SLs** production, due to the shorter duration of the main fermentation process
Aru & Ne (2018)	2nd generation biosurfactant in laboratory process	gate-to-gate	emissions from the **power supply** contribute the most to the overall environmental impacts the **intended application plays a key** role (in the investigated case, the production of large amounts of surfactant could be fully avoided)
Noll et al. (2024)	best-case scenarios of 4 different substrates for Di- rhamnolipids production RLs in limited scale (~30 m^3 bioreactor volume)	cradle-to-gate	**fatty acid-based substrates performed better** in the environmental assessment compared to **glucose and glycerol** **Energy consumption** is the most important hotspot **Composition of the energy mix** plays a decisive role in the impact on the environmental performance of the process. Environmental impact of **substrate production differs** (comparably high for soybean oil, stearic acid; rather low for glucose and glycerol)
Schonhoff et al. (2023)	RL and MEL production with substrate molasses (MOL) and sugar beet pulp (SBP), fermentation operation volume of 5000 L	cradle-to-gate	The use of molasses as a substrate for fermentation and the production of MEL provides the lowest potential environmental burden (LCA) and production cost (CA) **establishment of high recycling rates** of solvents used offers one of the highest improvement potentials within the process chain **Acetone production, ethyl acetate production, waste utilization, and compressed air supply** as well as the underlying specific flows (e.g., carbon dioxide or crude oil, etc.) were identified as the **main contributors** to environmental impact
Balina et al. (2023)	SL Fermentation; different prospective scenarios with different fermentation conditions and feedstocks, comparing raw cooking oil with waste cooking oil	cradle-to-gate	Use of waste cooking oil and process with energy efficiency reduce the environmental by 50% compared to base case (raw cooking oil, no further energy efficiency process compared to today) Main identified hotspots were electricity consumption and to a lesser extent the choice of lipid source in fermentation substrate

Obviously, available data make it difficult or even impossible to derive comprehensive conclusions regarding the sustainability of bio-based surfactants. Nevertheless, the studies indicate that certain processes, products, or applications may lead to interesting sustainability performance.

In particular, several studies highlight energy consumption as a key hotspot that influences the environmental impact. While, in general terms, second-generation biosurfactants were considered to require relatively less energy inputs (Albrecht et al., 2022), further optimization is key to reducing environmental impact.

Some results indicate the importance of the raw material used. Current second-generation surfactants on the market are still based on sugar. Moreover, agricultural practices have a significant impact on sustainability, and the impact of bio-based surfactants is disputed. Direct competition with food/feed use and potential land-use impact are prevailing concerns. LCAs usually do not cover land use changes that are especially relevant for the use of oils imported from third countries. These effects may influence the overall sustainability of bio-based surfactants. In addition, while the comparative advantage of second-generation biosurfactants compared to surfactants based on tropical oil is highlighted (see also in the text above), the current feedstocks used for first generation biosurfactants are diverse, and in comparison to those, e.g., the use of oils derived from animals, the environmental effects of second-generation biosurfactants are less clear.

3.4 Conclusion

Bio-based surfactants represent an important segment of bio-based chemicals. While bio-based feedstock has been utilized to some extent for surfactants in the past, the advent of biotechnology has opened new opportunities for second-generation biosurfactants. They have the potential to enhance the sustainability of surfactant production and use. They typically require low energy for production, exhibit low toxicity, are mostly fully biodegradable, and offer some unique performance characteristics. These advantages are not relevant for all applications and for certain applications these are partly fulfilled by other (conventional) surfactants as well. However, still there are applications where the characteristics of second-generation biosurfactants are of great value. Yet, the well know-barriers of higher prices and limited applications to date persist. It will be interesting to observe in the coming years to what extent biosurfactants will find their way between commodity chemicals and high-value-added applications.

In Germany, some large firms are at the forefront of the second-generation biosurfactant industry and may be able to maintain their favourable competitive positions, contributing to added value and job creation. In terms of environmental impact, the scarce existing information indicates that making general statements is challenging. Impact depends to a considerable extent on the feedstock used and substituted, as well as further optimization of processes. However, even in optimistic perspective, second-generation bio-based surfactants will likely remain a niche and may not directly lead to highly significant positive economic and ecological effects alone. Their importance may lie more in signalling the transition towards greener practices and acting as gate keepers for the production of higher-volume products with some green premium on the market. Our analysis also clearly indicates that the currently available data on environmental impact of second-generation biosurfactants is limited, only few full-fledged LCAs are available. Accordingly, more research efforts in this field would be beneficial.

4 Biopharmaceuticals

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4.1 Introduction

The first biopharmaceutical, humanized insulin produced in genetically modified E. coli bacteria (Goeddel et al., 1979), became available in 1982 (Buvailo, 2023). Since then, biopharmaceuticals are associated with a revolutionary treatment of diseases, including cancer, heart diseases, infections, arthritis, and multiple sclerosis (Bruun Rasmussen et al., 2021).

Historically, most medicines were plant extracts. Examples are quinine from the bark of a Peruvian tree (Cinchona officinalis) or artemisinin (from Artemisia annua) for the treatment of malaria, and salicylic acid as pain killer made from meadowsweet (*Filipendula ulmaria*) or from willow bark (Garcia, 2020). New developments in the tradition of plant-based active pharmaceutical ingredients (APIs) include the genetical modification of plants for the expression of proteins which do not exist in the natural form of the species, the so called "molecular farming" (Eidenberger et al., 2023).

Most biopharmaceuticals are now produced by recombinant DNA technology, whereby the gene of interest is transferred into a host organism, making the host produce the biopharmaceutical (Bruun Rasmussen et al., 2021). Bacteria, fungi, mammalian cells, but also plants and animals are used as host organisms for API production. Biopharmaceuticals represent a disruptive innovation compared to the established small-molecule medicines because tailor-made, personalized treatments adapted to specific characteristics e.g. of a particular type of cancer and the genetic information of an individual patient become possible (Makurvet, 2021).

Nevertheless, today, by far most pharmaceuticals are still developed and produced by means of traditional chemistry and based on fossil hydrocarbons as raw materials, resulting in so-called "small molecule" (SM) pharmaceuticals (Buvailo, 2023). Even medicines that earlier were derived from plants are now synthesized based on fossil carbohydrates for cost-effectiveness, quality, and standardization reasons.

4.1.1 Definition and characterization of biopharmaceuticals

Biopharmaceuticals (also known as "biologics") represent a unique therapeutic paradigm: they are derived from 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. They refer to large organic molecules or cells from biological sources, which are used as drugs with a therapeutic or preventive effect.

Biopharmaceuticals comprise several chemical classes of molecules. Major classes are recombinant proteins, e.g. monoclonal antibodies (mAbs), enzymes, hormones, blood components, vaccines, nucleic acid-based products (DNA, RNA) and genetically engineered cell-based products (e.g., stem cells). Not included are tissue-engineering products (Naumanen, 2019; Walsh & Walsh, 2022).

Bruun Rasmussen et al. define biopharmaceuticals as complex molecules derived from a biological source, with the purpose to diagnose, prevent, treat, or cure diseases or conditions of human beings (Bruun Rasmussen et al., 2021). They recommend to categorize them according to their biological structure (Bruun Rasmussen et al., 2021):

1) pharmaceuticals based on amino acids, including peptides and proteins,
2) pharmaceuticals based on nucleic acids, including oligonucleotides and plasmid DNA, and

3) vaccines, including whole-cell vaccines, subunit vaccines, and recombinant vector vaccines.

Some biopharmaceuticals fall under more than one main category, such as vaccines, which can be comprised of proteins and/or nucleic acids (Bruun Rasmussen et al., 2021).

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 product. Simpler biopharmaceuticals which do not require these modifications for their clinical effectiveness are often produced in nonmammalian and less expensive systems, such as fungi, bacteria and yeast (Makurvet, 2021).

Bacteria are advantageous for smaller proteins and peptides that do not require complex folding or post-translational modification. Proteins made in E. coli frequently need to be refolded from aggregated protein (inclusion bodies) after lysis of the cells. Yeasts can produce larger, more complex proteins, while mammalian cell lines – mostly Chinese Hamster Ovary (CHO) cells – are chosen for the largest proteins with complex folding and post-translation modification. Even the most complex proteins, such as a heterodimeric antibody, can now be produced in CHO cells with harvest concentrations exceeding 10 g/L, equivalent to what can be achieved in bacteria or yeast. High concentrations of the protein of interest lead to a lower contaminant load in the product stream (Puetz & Wurm, 2019).

Alternative production systems, such as transgenic animals or transgenic crop plants, have been developed in research for decades. However, their role for commercial manufacturing of biopharmaceuticals has so far been very small, especially because of the high requirements for approval of a totally novel production system (Eidenberger et al., 2023; Fausther-Bovendo & Kobinger, 2021). Cell-free systems for bio-based expression of proteins are also being developed (Makurvet, 2021).

Because of the complex production process of biologics compared with small molecules, the production costs and thus healthcare provider or end consumer prices are much higher (Buvailo, 2023; Makurvet, 2021).

4.1.2 Aim of the case study

The pharmaceutical industry is among the most resource-, energy-, and pollution-intensive industry sectors per unit of product mass (Etit et al., 2024).

Because of their intrinsically "biological" nature, expectations are high that biopharmaceuticals are more environmentally friendly than petrochemically produced small molecules, both in the extraction of their raw materials and in the disposal of resulting waste and pollution of wastewater with respective residuals (environmental sustainability). From a bio-based, circular production, economic gains compared to small molecule medicines might arise (economic sustainability). Improved health care and accessibility could even contribute to increased social sustainability.

The present case study analyses the potential benefits of biopharmaceuticals compared to SM medicines regarding their sustainability in the named three dimensions.

In particular, the following research questions will be answered:

- How large is the market for biopharmaceuticals and how will it develop?
- What are key factors for wide deployment?
- What kind of innovations are emerging until 2030/2040?
- Which economic, environmental, and social impacts result from biopharmaceuticals?
- By which indicators can these impacts and developments be described?

4.2 Market: current development and outlook

4.2.1 Market development

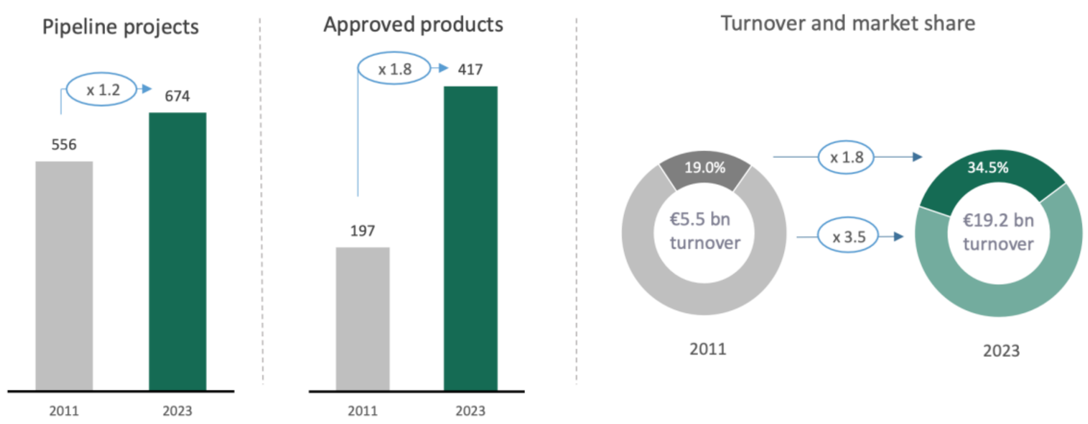
In 2022, companies in Germany had 674 biologics in clinical development. Vaccines experienced the highest growth rate with 11% more candidates than 2021 (Lücke & Bädeker, 2023).

Between 2017 and 2019, biopharmaceuticals accounted for more than half of the marketing authorisations in the EU (Albrecht & Kemper, 2020).

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 US$343.3 billion (Walsh & Walsh, 2022).

In Germany, 417 biopharmaceuticals had market approval by the end of 2023 (Lücke et al., 2024) (Figure 22). Biopharmaceuticals account for 34.5% of the whole pharmaceutical market and have strongly grown since 2011.

Figure 22: Development of biopharmaceuticals in Germany 2011-2023

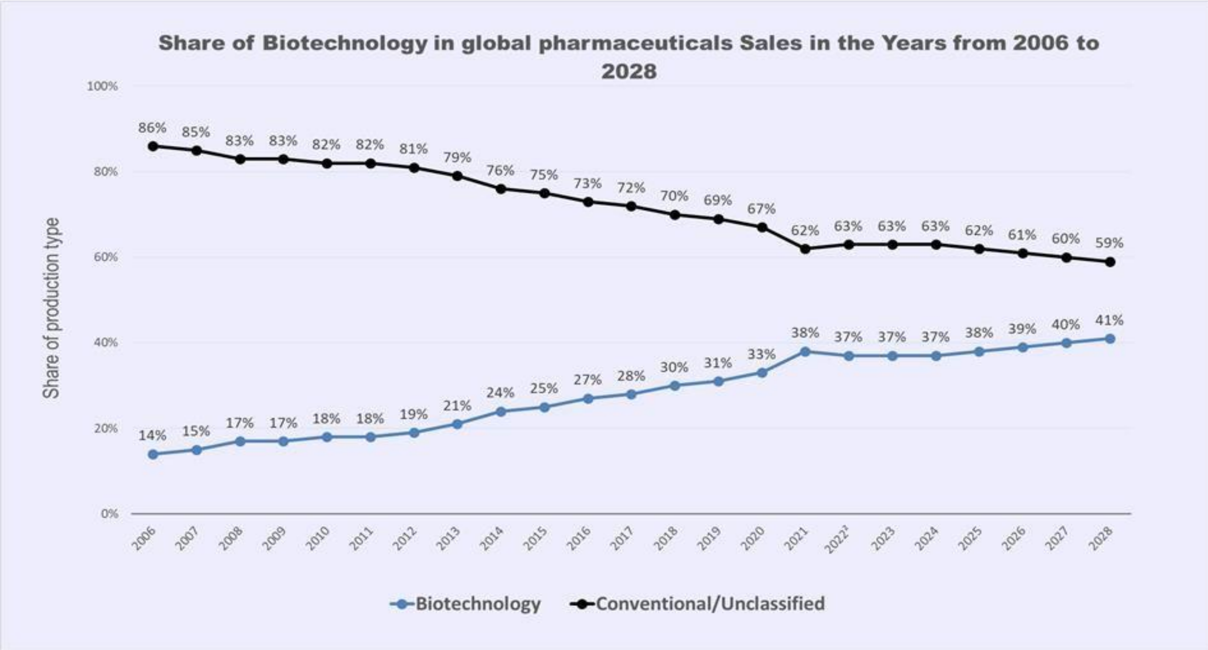


Source: Lücke et al. (2024)

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 & Walsh, 2022). The most dominant product group are monoclonal antibodies (mAbs). But with the Covid19 crisis, the mRNA vaccine *Comirnaty* (Pfizer/BioNTech) has become the top-selling biopharmaceutical in 2021, *Spikevac* (Moderna) is in third position according to market data (Walsh & Walsh, 2022).

The share of biopharmaceuticals in the total pharmaceutical market worldwide is about 37% now and expected to continuously increase (Figure 23).

Figure 23: Biopharmaceuticals share of the world-wide pharma turnover from 2006-2028



Source: Senior (2022)

In Germany, biopharmaceuticals generated a turnover of €17.8 bn in 2022, representing a share of 33% in overall pharmaceutical sales. The market for biopharmaceuticals has usually grown more than 10% per year in Germany which by far exceeds the total growth of pharmaceuticals. The turnover with biopharmaceuticals in Germany has more than tripled between 2012 and 2022 (Lücke & Bädeker, 2023).

Although, in numbers of treated patients, the sales figures for biopharmaceuticals are smaller than those for small molecules, biopharmaceuticals are by far stronger in terms of revenues. Only two biopharmaceutical drugs are found on the list of the 300 pharmaceuticals with highest number of prescriptions in the USA in 2021, Semaglutide, a peptide used as antidiabetic medication and as anti-obesity medication sold by NovoNordisk on rank 90, and Adalimumab by AbbVie, a monoclonal antibody used to treat rheumatoid arthritis and other autoimmune diseases on rank 236 (ClinCalc.com, n.d.).

Among the 10 drugs with highest sales volume worldwide in 2023, however, eight were biopharmaceuticals, and all of the top five, among them monoclonal antibodies, RNA vaccines and peptides (Statista, 2024).

Biopharmaceuticals are a segment with very high value added, and highly industrialized countries have an advantage in competition. This is due to location factors like highly skilled people and the existence of regulatory settings and control that fulfil global requirements for potential exports. Germany has a rather strong position in research and development but also plays 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 (vfabio, 2020). For a long time, Germany also possessed the second largest fermentation capacity in the world behind the US However, according to the latest available information for 2018, South Korea has surpassed 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 & Yagüe-Perales, 2021). Moreover, the gap between

R&D expenditures in the USA and the European countries has risen enormously (Wilsdon et al., 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, because the natural variability and 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 European Medicines Agency (EMA) approved the first biosimilar in 2006 (European Medicines Agency, n.d.). 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 significant cost savings in reimbursements and thus improved patient access to treatment with biopharmaceuticals. In the past decades, the biosimilar 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 (Israel) and Cipla (India). 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).

Regarding future market development it can be stated that biopharmaceuticals already dominate in terms of turnover e.g. for immunology or sense organs, and almost present half of the turnover for oncology and metabolism (Lücke et al., 2022). Recently, higher attention has been given to vaccines, as those for Covid19 were all developed by biotechnological methods. During the pandemic, the biotech sector impressively demonstrated how rapid it 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.

The growth and increasing importance of biopharmaceuticals compared to the – still growing – overall pharmaceutical market is likely to continue because of a strong innovation pipeline and the still increasing importance of biosimilars (Troein et al., 2021). It is estimated that the share of biopharmaceuticals of total worldwide prescription drugs and over the counter sales will rise from 37% in 2023 to about 41% in 2028 (Senior, 2022).

The sector faces a large set of expiring patents in the next ten years, as mega-blockbusters including Humira®, Keytruda®, Opdivo® and Eliquis® lose patent protection and therefore the producers' revenues generated with these drugs will sink considerably. Niche drugs still dominate the pipeline, particularly in oncology and for rare diseases. On the other hand, new treatments e.g. for obesity or Alzheimer's disease promise much greater numbers of patients. The obesity market is growing; forecasts put combined obesity sales in 2028 above US$11 billion (Senior, 2022), and in ageing societies a similar development can be expected for Alzheimer's disease and other neurodegenerative diseases. Most of 2028's top 10 drugs are expected to be biotechnology-based (Senior, 2022).

4.2.2 Drivers and barriers

Factors driving the bio-based transformation of the pharmaceutical industry include changes in demographic structures and consumer preferences in industrialized and emerging economies, as well as advances in biotechnology and medical research. In response to growing middle-income classes and increased consumer awareness, companies have also increased research in "personalized" medical solutions (Stark et al., 2022).

The development of specific therapies for small patient groups based on established platform technologies is expected to continue, but a movement to larger unmet needs like Alzheimer's disease and overweight can already be observed (Senior, 2022). Private funding of biopharmaceutical R&D continues to break records, reaching almost US$13 billion in the first half of 2022 only, anticipating the sector's continued relevance (Senior, 2022).

Climate change is increasing the risk for the transmission of various infectious diseases. Vectors earlier restricted to the tropics are spreading globally and even to tempered climate zones like Europe and Northern America, as already can be observed e.g. for pathogenic non-cholerae Vibrio, dengue fever, and West Nile virus in Europe and Northern America (Nolen, 2023; van Daalen et al., 2022), fostering the need for biotechnologically developed and produced vaccines. Dengue fever is one example for which therapeutics and vaccines are under development (WHO, 2023). Two vaccines have received marketing authorisation in the EU and several others are in the pipeline, nearly all of them including steps of recombinant protein, DNA or other methods of biotechnology (Reuters, 2023; Torres-Flores et al., 2022).

Compared to other bio-based industrial products, biopharmaceuticals are extremely high-value and very low-volume products, which implies the following impacts (Table 7).

Table 7: Drivers and barriers for market Development

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., digitalization, 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: • 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)	Extremely high costs for several biopharmaceuticals, especially for rare diseases. Public 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 & Walsh (2022); Baltruks (2023)

4.3 Economic, environmental, and social impacts

Sustainable development includes three core elements: economic development, social inclusion, and environmental protection, all of which climate change is closely interlinked with (United Nations, n.d.-b). The United Nations formulated 17 interlinked Sustainable Development Goals (SDGs) to reach peace and prosperity for people and the planet (United Nations, n.d.-a). The following chapter reviews the impacts of biopharmaceuticals along these three dimensions. Biopharmaceuticals and small molecule medicines mostly have different target conditions; only in rare cases can biopharmaceuticals replace small molecules directly. Head-to-head-comparisons are therefore hard to do. The focus here rather lies on the impacts of a further increase of biopharmaceuticals and potentials to improve their sustainability in R&D and application.

4.3.1 Economic impacts

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 (SDG 8, Decent Work and Economic Growth; SDG 9, Industry, Innovation and Infrastructure). While the number of firms has only grown to some extent in the last decade, the number of employed persons related to biopharmaceuticals has risen from 28,000 in 2011 to 50,000 in 2022 in Germany (Lücke et al., 2022; Lücke & Bädeker, 2023), more than any other processing industry in the bioeconomy.

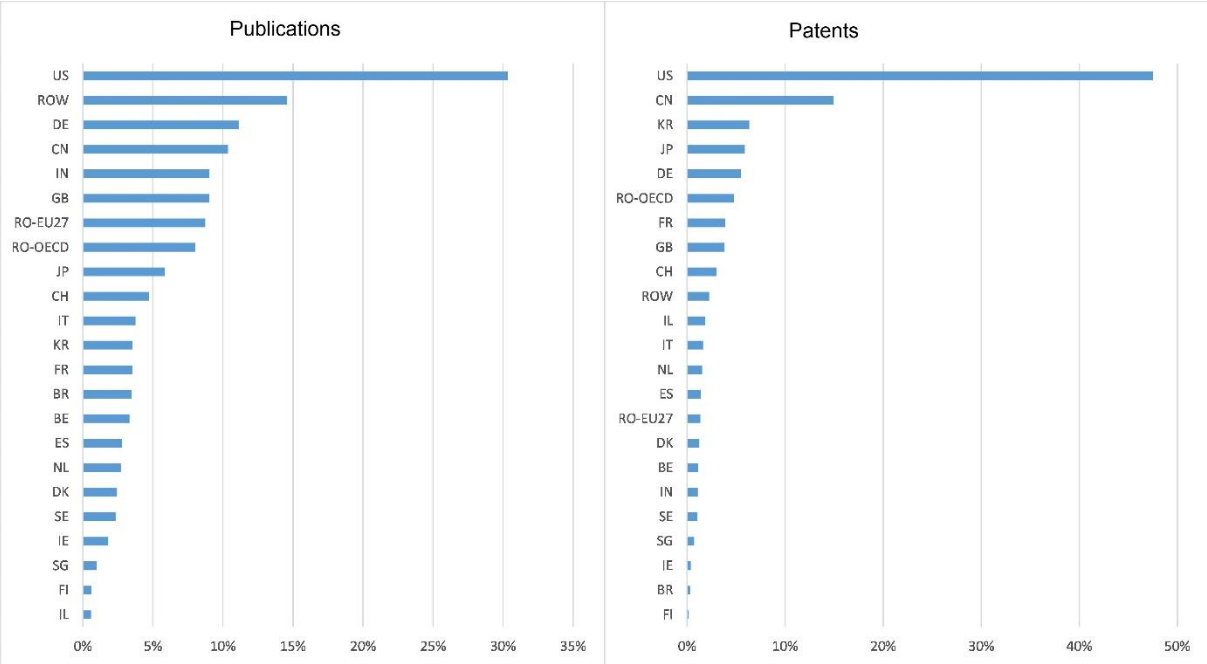
Despite frequent claims that value creation did not occur in Germany, Covid19 vaccines recently demonstrated biopharmaceutical production also in Germany. With the most recent discussion on European technological sovereignty and resilience it can be assumed that the trend towards relocating production capacities from Europe to non-European countries will slow down or even be reversed in the future.

4.3.1.1 Innovation activities

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, 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 & Walsh, 2022). This underlines the innovative potential of this class of pharmaceuticals.

Reiß et al. (2023) analysed the innovation activities in Germany as compared to other areas with a focus on four biopharmaceutical areas: gene and cell therapy, RNA-technologies, biologicals/biosimilars, and vaccines, as well as small molecules. The analysis of German strengths in competition regarding science, technology and export/import showed that the German position is at best average, if not slightly below average in nearly all fields. The exception are biologicals/biosimilars, where the German position in international competition is above average. In all four fields of technology, Germany shows better results in scientific activities indicated by scientific publications than in technology development, as measured in patent applications (Figure 24).

Figure 24: Selected countries' share of world-wide publications and patents in biopharmaceuticals, 2019-2021



Source: Reiß et al. (2023) based on Elsevier - Scopus; EPA – PATSTAT; ROW: Rest of world; RO-EU27: Rest of EU-27; RO-OECD: Rest of OECD

Leading in all technology fields are the USA. China has a strong scientific profile in some fields, particularly in RNA-technologies. The entire picture including publications, patents and trade is below average for China, however. Besides the USA, in cell and gene therapy, the UK, Switzerland, South Korea, and Israel are leading. Denmark, Israel, and South Korea, as well as the USA, have strong positions regarding RNA-technologies. In the field of small molecules, the strong position of India stands out, but also other countries with an established pharma sector as e.g., Switzerland, Denmark, and the UK are well positioned. This is also true for Switzerland and the UK with regard to vaccines, but also India or Belgium is very successful in this field. Even for biologicals/biosimilars countries with a strong pharma sector show results above average, as e.g. the UK, Denmark, or Switzerland (Reiß et al., 2023).

4.3.1.2 Efficiency of manufacturing processes

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.

Even for the most broadly established production system, mammalian cells, opportunities for further development exist through further advancements in production systems as well as through vector and host cell engineering (Paulick et al., 2022; Wurm, 2004).

A priority is the intensification of manufacturing processes, 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). Combinations of fed-batch and multi-use equipment yielded the best cost-benefit ratio for cultivation systems. Further improvements to cell's growth characteristics such as the specific production rate have a high potential to enhance the cost−benefit of mAb cultivation (Amasawa et al., 2021).

A life-cycle assessment (LCA) showed that a shift from conventional to single-use bioprocessing technology can result in substantial reductions in global warming potential, cumulative energy demand, water usage, and other environmental impacts for the production of monoclonal antibodies. Although single-use bioprocessing technology needs the production, distribution, and disposal of its components, it reduces or eliminates the need for large quantities of steam, process water and sterile water for injection and therefore single-use bioprocess train has lower environmental impacts compared to the conventional process train (Cytiva, 2020).

Substantial savings of water use and carbon emissions are possible through optimization of production processes (Cataldo et al., 2020).

Even other aspects of the production technology can reduce the use of water and other solvents, like novel polymers for efficient purification of biopharmaceuticals (del Castillo et al., 2022).

Media for cultures with animal cells are likely 100–1000-fold more expensive than those for cultures of bacteria or fungi (Puetz & Wurm, 2019). Eliminating animal-derived compounds of culture media can reduce the cumulative resource consumption of monoclonal antibody manufacturing by up to 7.5 times (Renteria Gamiz et al., 2019).

4.3.1.3 Digitalisation and integration of AI technologies

A key driver for future development and economic benefits of biopharmaceuticals will come from AI technologies. Innovation in biopharmaceuticals and all aspects of the pharmaceutical value chain are impacted by the digital transformation in life sciences. AI has the potential to substantially reduce the consumption of resources in biopharma development and production and thus increase their sustainability, but the EU is increasingly lagging behind the USA in development and application of AI (Wilsdon et al., 2022).

Silva et al. (2020) analysed the potential gains of and barriers to the implementation of Industry 4.0 principles in the biopharmaceutical sector. The goals of an integration between the virtual and the real world are a greater degree of automation and digitization of processes. Technologies used include:

- automation,
- machine to machine communication,
- artificial intelligence (AI),
- big data analyses,
- cloud computing,
- systems integration, and
- cybersecurity.

Most important potential benefits that were found in the literature and expert interviews were:

- gains related to performance and productivity, mostly related to the increase in operational efficiency (e.g., by rigorous real-time monitoring) and production capacity,
- advantages related to competitiveness, such as greater possibilities for customization, better meeting deadlines and reduced time to market,
- better complying with regulatory aspects and social and environmental responsibilities.

Barriers for a progress towards Industry 4.0 in biopharma were seen in:

- the need to break organizational cultural standards,
- regulatory requirements,
- a lack of organizational strategies for implementation,
- a lack of qualified professionals.

In biopharma, the search for new targets and respective APIs is particularly resource-intensive because of the big size of the molecules. AI technologies could improve the efficiency of research and reduce the still high failure rate of drug candidates in phase I clinical trials that do not reach marketing authorization (Smalley, 2017). Therefore, 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).

Machine learning can be applied in all stages of drug discovery, e.g. target validation, identification of prognostic biomarkers or analysis of data from clinical trials. Yet, interpretability and repeatability of results generated with machine learning are still unclear. The models rely on systematic and comprehensive high-dimensional data which still need to be generated. With these issues solved, the application of machine learning has the potential to speed up the process and reduce failure rates in drug discovery and development (Vamathevan et al., 2019). Machine learning makes processes more effective and saves work and resources and thus has the potential for cheaper and more eco-friendly development and production of APIs (Makurvet, 2021; Paulick et al., 2022).

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).

4.3.2 Environmental impacts

Awareness has risen internationally that the healthcare sector is responsible for a substantial share of resource consumption and greenhouse gas emissions (Karliner, 2019; Lenzen et al., 2020), putting pressure on reducing the environmental impacts of biopharmaceutical manufacturing and delivery (SDGs 14, Life below Water; 15, Life on Land; 13, Climate Action). However, the pharmaceutical industry has only started to address its environmental footprint (Okereke, 2021). Robust analyses of environmental impacts of pharmaceuticals are rare; Etit et al. (2024) estimate, that environmental sustainability assessments have only been conducted for approximately 0.2% of the more than 20 000 Food and Drug Administration–approved drugs.

In Germany, healthcare 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, 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 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 authorization (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).

But still, environmental impact assessments for medicinal products in the EU only have the aim of "protecting aquatic and terrestrial ecosystems including surface water, groundwater, soil, species at risk of secondary poisoning and the risk for the microbial processes in sewage treatment plants" (Guideline on the Environmental Risk Assessment of Medicinal Products for Human Use, 2024). Aspects of climate change, energy production and resource consumption are not covered.

Biopharmaceuticals have less effects of changed land use than other fields of the bioeconomy. However, potential effects occur in CO_2 emissions for energy, use of water, 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)[12] 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, water use is the single greatest contributing factor to the environmental impact (see below).

4.3.2.1 Greenhouse gas emissions

Climate change is the single biggest health threat facing humanity, projected to cause 250,000 additional deaths per year, and healthcare is responsible for 4.4% of global emissions (Belkhir, 2019). While the largest pharmaceutical companies have established zero carbon goals and work to reduce emissions (Booth et al., 2023), by far the largest part of the global pharmaceutical and biotech industry has yet to set any targets for reducing carbon emissions in line with the Paris Agreement. The total carbon impact of the industry has continued to increase (Connelly et al., 2023).

The variation between companies even with similar product portfolios is huge, indicating that different management and production processes can lead to substantial GHG reductions. In order to comply with the reduction targets in the Paris Agreement, the overall pharma sector would need to reduce its emissions intensity by about 59% from 2015 levels by 2025 (Belkhir, 2019).

The use of living cells and viruses to manufacture pharmaceutical products implies the necessity for adequately tempered clean rooms and thus high energy consumption for heating, ventilation and air conditioning (HVAC). HVAC consumes from 50-80% of the energy in a typical clean manufacturing facility. The more highly classified the space, the higher is the percentage of energy use. Some extra effort up-front can result in facilities that consume less energy, emit less carbon and cost less to operate than more traditional designs (Goldschmidt, 2021).

Cell culture media ingredients are today partly made of bovine serum. Since mammalian cell lines permit post-translational modification of the proteins, proteins created with animal-based supplements or in mammalian cells closely resemble their natural counterparts. Therefore, they can provide better functionality and reduce the possibility of adverse immunological reactions than non-mammalian ingredients or proteins from other cell types (Merck KGaA, 2024)

However, rearing farm animals, in particular ruminants, results in large emissions of greenhouse gases (GHG), in particular CO_2 and methane from ruminants' digestion tract, but also N_2O and NH_3 from fertilizer and – occasionally – GHG from changes in land use, e.g. when forest or peat lands are turned into areas for growing animal feed. In 2015, livestock accounted for about 12% of the estimated total anthropogenic emissions, and cattle are the primary contributors to GHG emissions (FAO, 2023). Replacing bovine serum as ingredient to cell culture media would thus substantially reduce the GHG emissions related to biopharmaceuticals production.

Etit et al. (2024) distinguish four routes of pharmaceutical production based on the selected feedstock (nonrenewable or renewable) and the processing route (synthesis vs. extraction/semisynthesis for non-renewable raw materials or extraction/semisynthesis vs. fermentation or enzymatic biocatalysis for renewable raw materials. In this analysis, fermentation-based processing was observed to have by far the highest mean climate change impact, followed by extraction/semisynthesis routes

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

and chemical synthesis. Among the fermentation-based products, it was particularly the monoclonal antibodies, which had significantly higher climate change impacts compared with the remaining fermentation products (pharmaceutical enzymes, penicillin). With mAbs excluded, fermentation routes resulted in a lower climate change impact than most synthetic/semisynthetic products. The authors conclude that substituting animal-sourced materials in the production media can significantly reduce the environmental impacts of mAb production (Etit et al., 2024).

4.3.2.2 Water consumption and waste production

Water usage in biopharmaceutical production may be >100-fold higher of that used in small molecule manufacturing (Ho et al., 2010). A typical 20,000 L batch-based production facility may need more than 5.5 million litres of water per year, especially for downstream product purification (Kokai-Kun, 2022). Batch production lines were compared to continuous production in a cost-benefit analysis by Amasawa et al. (2021). In batch production, bioreactors can either be disposed of after each batch (single-use reactor) or need costly cleaning before reuse (multi-use reactor) with more or less production of waste or use of chemicals and water, respectively, which result in different impacts on human health, e.g. by emission of risky pollutants. The results showed a trade-off between the operating cost and human health among different process scenarios. Continuous modes had the least negative impacts on human health but the highest operating costs, while the combination of fed-batch and multi-use equipment yielded the lowest operating cost with the highest human health damage (Amasawa et al., 2021).

On the other hand, a 2007 cost study concluded that switching from batch processing to continuous downstream processing of monoclonal antibodies could reduce operational costs by almost 70%. Continuous technologies are available at different production stages (Holzer, 2017). Specific solutions and combinations of batch and continuous methods are being employed (Newton, 2022).

In a life-cycle analysis for single-use products in the production of biologics, Budzinski et al. (2022) found that the ecological footprint of single-use products made from plastic was small compared to the electricity used to operate the plant. They conclude that operational changes that increase process efficiency and decrease time in plant are among the best strategies for reducing the life cycle environmental impact of biologics manufacturing.

4.3.2.3 Environmental pollution

Relevant research regarding environmental risk assessment of biopharmaceuticals is scarce (Bruun Rasmussen et al., 2021).

Compared to small-molecule drugs, manufacturing therapeutic proteins requires very small amounts of solvents (except water), especially hazardous ones. The amounts of solid waste generated are comparable between the two groups (Ho et al., 2010).

In 2009, the European Environment Agency (EEA) hosted an expert workshop on pharmaceuticals in the environment. The workshop addressed a variety of issues, including the magnitude of the pharmaceuticals market and the amounts of pharmaceutically active substances produced, detected or assumed environmental effects, and ways to reduce impacts. Climate change was not an issue at all at the workshop. The experts concluded that the rapid expansion of the biopharmaceuticals area will contribute to major reductions in environmental residues (European Environment Agency, 2010).

Because of a supposed rapid degradation, biopharmaceuticals consisting of naturally occurring substances (amino acids, peptides or proteins) are considered as less hazardous by the European Medicines Agency and an environmental risk assessment (ERA) before marketing authorisation is not obligatory for this group of active substances. Peptides and proteins that have been structurally modified using non-natural amino acids to increase biostability, on the other hand, are considered non-natural and therefore have to undergo such an ERA, which only considers ecotoxicity (Guideline on the Environmental Risk Assessment of Medicinal Products for Human Use, 2024).

Despite their biological origin, even biopharmaceuticals can contribute to environmental pollution. Some protein structures like prions are known to be very stable, and even smaller changes in the chemical structure of an API may have a significant impact on its solubility and polarity as well as other properties that govern their environmental fate. The risk assessment has to include secondary molecules that emerge from the API while it is metabolized in the body or transformed through external factors after excretion as well as adjuvants used in combination with the API (Kümmerer, 2009).

Bruun-Rasmussen et al. (2021) find that the scientific evidence for excluding a whole class of products from ERA is too weak and propose a case-by-case appraisal of the necessity for an ERA even for proteins as biopharmaceuticals.

4.3.2.4 Replacing animal-based by plant-based production systems

While one chicken egg can produce one or two doses of flu vaccine, one tobacco plant can produce 50 at a fraction of the cost and result in much higher yields in shorter time (Begley, 2014).

Although vaccines, antibodies, and therapeutic proteins have been produced in plants, such pharmaceuticals are not readily utilized by humans due to differences in glycosylation, and few such compounds have been approved due to a lack of clinical data (Lee et al., 2023). First successes have been reached: A plant-derived therapeutic protein for human use was approved in 2012 for the treatment of Gaucher disease. In 2019, a plant-produced influenza virus vaccine completed phase III clinical trials, and in March 2021 phase III trials for a plant-made vaccine against SARS-CoV-2 began (Fausther-Bovendo & Kobinger, 2021).

It is expected that plant systems will become widely used as expression systems for recombinant protein production (Lee et al., 2023).

4.3.3 Social impacts

4.3.3.1 Improvements in health and well-being

The main potential value of biopharmaceuticals regarding social sustainability is an increase of health and well-being. The functional diversification and increased effectiveness of medical treatments represent an obvious direct contribution of biopharmaceutical transformations to sustainability, particularly to SDG 3, Good Health and Well-being (Stark et al., 2022). Biopharmaceuticals have the potential to address unmet medical needs and enable novel therapies also for rare diseases. The COVID19 pandemic gave an impressive example for the flexibility of the biopharmaceutical sector to quickly respond to an urgent medical need.

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.

4.3.3.2 Equitable social development

Because of their high sales price, biopharmaceuticals are less easily available in low-income countries than small-molecule medicines and thus their social sustainability regarding SDGs 3 (Good Health and Wellbeing) and 10 (Reduced Inequalities) regarding access to them is lower. "Biosimilars", which differ in their active ingredient although they resemble an original biopharmaceutical and have the same therapeutic function, have in general the same development costs as their original counterparts, in particular because of the equally expensive clinical testing (Cohen et al., 2023). Because of their role as competitors to the original product, however, they can substantially reduce sales prices and thus improve access to biopharmaceutical treatments (European Commission, 2023; Makurvet, 2021).

In comparison with original biopharmaceuticals, healthcare expenditures can be reduced by biosimilars. This would be particularly important for diseases that require biopharmaceutical products for potentially life-long treatment with ever-increasing prices for new medicines, where the high level of drug spending otherwise could even threaten the sustainability of healthcare systems (Schreiber et al., 2022). This is an important issue not only in low-income countries but also in EU member states. Policies to eliminate barriers to entry, adoption, and utilization of biosimilars would foster access of patients to novel and affordable treatments, increased competition would drive technical innovation (European Commission, 2024).

Biological processing offers wider accessibility of pharmaceuticals by a decentralized and flexible biomanufacturing supply chain, especially via independent and trustable microbial refactoring routes which could replace location-dependent plant extraction processes that are unstable and expensive (Etit et al., 2024).

Positive secondary effects to achieve SDGs 4 (Quality Education) and 8 (Decent Work and Economic Growth), e.g., are anticipated from potential related investments in educational and vocational training programmes and from increased employment opportunities in the sector. Given signs of a beginning gradual shift in the geographical balance of the pharmaceutical market towards emerging economies, such benefits may also accrue in the developing world (Stark et al., 2022).

4.4 Conclusion

Biopharmaceuticals represent a disruptive innovation compared to the established small-molecule medicines because tailor-made, personalized treatments adapted to specific characteristics e.g., of a particular type of cancer or the genetic information of an individual patient become possible.

The economic impact of biopharmaceuticals mainly results from direct value added and employment in the biopharmaceutical industry and to a certain extent from indirect effects throughout the value chain and an increased healthy workforce. Economic sustainability of biopharmaceuticals emerges through their increasing importance and continuing market growth. To which extent Europe and Germany can benefit from this development is still to see: Regarding publications in the field of biopharmaceuticals, Germany was able to follow the worldwide upward trend, but regarding patents, a decrease has to be noted within the last decade.

Environmental sustainability advantages of biopharmaceuticals compared to small molecule medicines are difficult to assess because of their different nature, production process and area of application (target diseases). Generally, biopharmaceuticals consisting of naturally occurring substances (amino acids, peptides, proteins, particles of RNA or DNA) are considered as less hazardous than small-molecule drugs. Biologically generated raw materials for biopharmaceuticals have the potential to reduce the industry’s greenhouse gas emissions and use of hazardous substances. However, for instance, water usage in biopharmaceutical production is usually much higher than in small molecule manufacturing.

Changes in raw materials, the integration of AI in drug development as well as improved manufacturing have the potential to further increase the sustainability of biopharmaceuticals.

Regarding social impact, the functional diversification and increased effectiveness of medical treatments represent an obvious direct contribution of biopharmaceuticals to social sustainability. Biological processing offers wider accessibility of pharmaceuticals by decentralized and flexible workforce development, R&D, and biomanufacturing supply chains. Because of their high sales price, biopharmaceuticals are less easily available in low-income countries than small-molecule medicines and thus their social sustainability regarding access is lower.

Concerning measurement of innovations in the bioeconomy, biopharmaceuticals are a special case, as unique market data exists, which is not available for other bioeconomy markets. Based on data collected for regulatory purposes, the number and share of biopharmaceuticals in clinical trials, the share in new molecule entities (NME) authorized and share of biopharmaceuticals in the market are relevant indicators. Moreover, dedicated regular studies exist which analyse employment for biopharmaceuticals over time and more in-depth than cross-sectoral studies do in other sectors. However, aggregate information on environmental effects is scarce and the often unique production settings make it difficult to come to overall conclusions.

5 Alternative meat

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5.1 Introduction

A growing world population and increasing prosperity are leading to rising demand for animal derived food and meat. However, expanding conventional agricultural livestock farming would increase its negative effects on the environment, climate, animal welfare and human health and compromise the urgently needed sustainability transition of the agro-food sector. As one potential solution meat alternatives are being developed. They mimic meat products in appearance, taste, texture, and cooking practices but do not rely on traditional livestock farming. Different options have emerged with plant-based meat, and cultivated meat as the most prominent ones. Those meat alternatives could contribute to meet the demand for meat, but significantly reducing land use for meat production, and transforming value chains. However, many uncertainties occur regarding future market evolution and impacts of meat alternatives. Among others, this is due to the high diversity of potential feedstocks, conversion methods and products, their nascent technological state, current limited market pervasiveness and complex regulatory frameworks.

5.1.1 Aim of the case study

The aim of the case study is first to characterize current and potential future markets and industrial developments in this highly dynamic field. In addition, a synthesis of potential economic and ecological impacts is provided. Here, the aim is also to delineate likely emerging paths of meat alternatives and the overall macro-economic and ecological impact. Therefore, we aim to delineate consistent plausible assumptions based on data and literature for input parameters for further modelling in the SYMOBIO2.0 project, which are shown in the Annex and were taken as basis for scenario modelling in Lutz et al. (2024). As the timeframe of the modelling is until 2030 and 2040 respectively, we adopt this perspective. We focus mainly on plant-based meat alternatives (PBMAs) as these have most likely by far the highest impact on the value chain. Moreover, we consider cultivated meat, especially as a potential alternative in the long-term with significant different structural implications compared to PBMA. We do not consider other alternatives (e.g., insects) as these rather unlikely will have a significant diffusion and impact in the next 10 to 20 years.

5.1.2 Definition and characterization of meat alternatives

5.1.2.1 Plant-based meat alternatives

Plant-based meat alternatives (PBMAs) are innovative food products which mimic meat products in appearance, taste, texture, and cooking practices. The basis for PBMA are plant proteins, isolated from agriculturally grown crop plants such as wheat, soybeans, peas, and beans.

PBMAs have been available commercially for decades (Aiking et al., 2006), if not centuries (Shurtleff et al., 2014). While remaining a niche phenomenon for years, it was only in the recent past that PBMAs gained momentum. Instead to the "simple" process of raising and slaughtering animals and processing their flesh by cutting, boiling, curing etc., the production of PBMAs involves a distinct degree of food technology.

Ultimately, while PBMAs constitute ultra-processed foodstuffs, its initial feedstock and underlying production technologies at large have a long record of use in the food industry. For example, in addition to producing textured vegetable protein, extrusion has typically been used to produce foodstuffs such as pasta, cereals or sausages. From a technological perspective, PBMAs thus feature a clearly higher degree of technological maturity than cultivated meat (CM).

5.1.2.2 Cultivated meat (CM)

Cultivated meat (CM) is produced by cultivating animal cell lines in bioreactors under controlled conditions. Compared to PBMAs, CM features a much shorter history, with first ideas of producing specific meat products without having to raise and slaughter animals allegedly dating back to the beginning of the 20th century (Bhat and Fayaz, 2010). Apart from earlier experimental products (e.g., Bethge, 2005), CM first entered the wider public frame with Mark Post[13]'s 2014 public tasting of CM burger patties.

In addition, the technologies upon which CM production draws, are more complex than those behind PBMAs. CM draws from advanced technologies such as cell-culture techniques, biomanufacturing methods, or growth factors and ingredients produced with genetically engineered microorganisms. Put briefly, CM production means the in-vitro cultivation of animal stem cells into tissue by means of technologies originally developed for bio-medical applications (Post et al., 2020; Good Food Institute, n.d.). Due to the relative novelty of the notion of CM, CM production technology is linked to risks and uncertainty, e.g. regarding up-scaling (Sinke et al., 2023). In the same vein, there remains ample room for technological improvement (Good Food Institute, n.d.).

5.2 Market: current development and outlook

5.2.1 Market development and key producers

Plant-based meat alternatives (PBMAs)

The global plant-based meat market is estimated to US$7.9 billion in 2022 and is predicted to experience a compound annual growth rate (CAGR) of 14.7% from 2022 to 2027 (Markets and Markets, 2022). The estimates provided by the highly cited study of BCG & Blue Horizon (2021) for 2021 are similar to this estimate but slightly lower: They anticipate the overall alternative protein market to grow at a base case rate of 14% CAGR from US$13 billion in 2020 to US$32.5 billion in 2027, with around one-third of this attributed to alternative meats (BCG and Blue Horizon, 2021). In this context, 'alternative meat' refers to plant-based meat, as BCG and Blue Horizon expect animal cell-based proteins, including cultivated meat, to begin gaining market share only at a later time.

Table 8: Top companies in global alternative meat market

Type	Companies	Origin	Establishment year
Plant-based meat alternatives (PBMAs)	Beyond Meat	US	2009
	Kellogg Company	US	
	Impossible Foods Inc.	US	2011
	Maple Leaf Foods	Canada	
	Unilever	UK	
	Conagra Foods	US	
	Tofurky	US	1980

[13] Mark Post from Maastricht University is one of the promotors of CM in Europe, he co-founded Mosa Meet (see table 8)

Type	Companies	Origin	Establishment year
	Gold&Green Foods Ltd.	Finland	2015
	Sunfed	New Zealand	2015
	Monde Nissin	Philippines	
Cultivated meat (CM)	Mosa Meat	Netherlands	2013
	Upside Foods	US	2015
	Just Inc.	US	
	Integriculture Inc.	Japan	
	BioCraft Inc.	US	

Source: Markets and Markets (2022), Markets and Markets (2023)

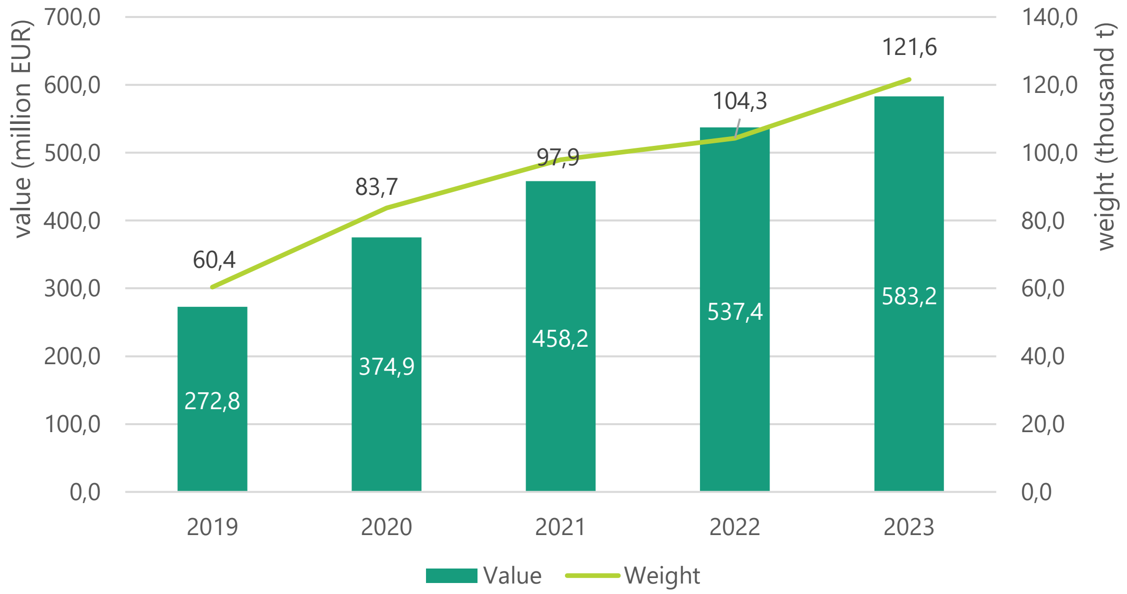
Geographically, North America, being the fastest-growing region for plant-based meats (Markets and Markets, 2022), serves as the birthplace for many of the largest manufacturers, as depicted in Table 8. Among these, Beyond Meat, Impossible Foods Inc., Tofurky, Gold&Green Foods Ltd, and Sunfed stand out, with plant-based protein constituting their primary business focus. It's noteworthy that the majority of these companies emerged during the six-year span from 2009 to 2015, originating as startups. But also large established food companies such as Kellog Company are active in this market.

In Europe, many producers of plant-based meat alternatives are subsidiaries of large traditional meat producers specifically established to enter the alternative meat market. As illustrated in Table 9, traditional meat producers from Ireland, the UK, Germany, Denmark, the Netherlands, and Spain are actively embracing meat alternatives or exploring the future of meat (vegconomist, 2024a; vegconomist, 2024b; vegconomist, 2024c). According to EY, traditional meat producers are under pressure to transform in order to remain relevant in the long term (Krupke, 2023). These companies can capitalize on their expertise in meat production, deep understanding of meat consumers, and established supply chains to penetrate the plant-based meat market (Krupke, 2023). Moreover, they stand to benefit from brand spillover effects, especially among consumers who are open to traditional meat but seek to reduce their overall meat consumption (Krupke, 2023). For example, Germany's Rügenwalder Mühle was the first among those listed in Table 9 to enter the plant-based meat market, achieving a significant leadership position with over 40% market share (Krupke, 2023).

In Germany, plant-based meat alternatives have been classified as a separate product group in official statistics since 2019. As a result, they are among the few innovative products in the bioeconomy explicitly tracked in official statistics. The data indicate a continuous increase in both the turnover and the production volume of meat alternatives over the past four years. In 2023, turnover exceeded €580 million per year (Statistisches Bundesamt, 2024b).[14] Additionally, the number of active companies increased from 33 in 2019 to 67 in 2023. Figure 25 below illustrates the turnover and production volume in Germany.

[14] It is important to note that the value is calculated based on the ex-works sales price achieved during the reporting period or attainable at the time of sale. This includes the cost of packaging but excludes sales and excise taxes, as well as separately invoiced freight costs and discounts.

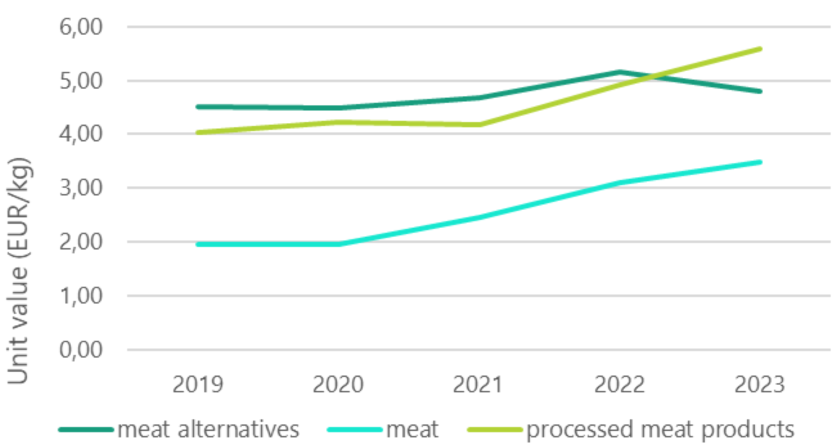
Figure 25: Development of meat alternatives production in Germany



Source: Statistisches Bundesamt (2024a)

Despite the strong growth of meat alternatives, their value and production still lag far behind that of meat[15], comprising only about 1/80 of the latter. Interestingly, the unit values of alternative meat and real meat are slowly converging, as illustrated in Figure 26, which may lead to alternative meat becoming more competitively priced in the future. Furthermore, when comparing alternative meat with processed meat products, the difference in unit value is not significant and falls within an acceptable range in Germany. At a first glance surprisingly, the average annual production per company for alternative meat surpasses the production rate of traditional meat in 2023 (Figure 27). However, considering the by far larger number of traditional meat producer (~10.000) vs. alternative meat (67) such a comparison should be made carefully as industry structures of mass production typically differs from niche production.

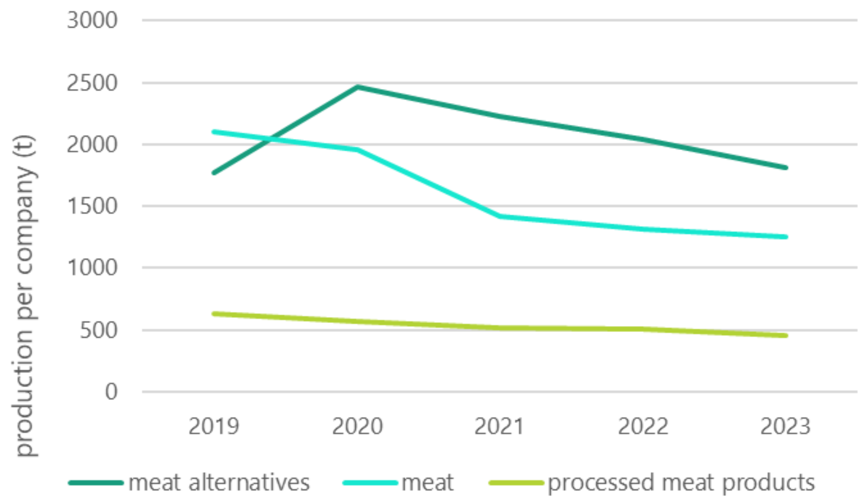
Figure 26: Unit value of meat and alternative meat in Germany



Source: Statistisches Bundesamt (2024a)

[15] Meat includes fresh/frozen meat (incl. other fresh/frozen animal products, such as organs, fat, etc.) and processed meat products; specific classifications can be found in the appendix.

Figure 27: Meat and alternative meat production per company in Germany



Source: Statistisches Bundesamt (2024a)

Cultivated meat (CM)

The global cultivated meat market is anticipated to reach a value of US$0.2 billion in 2023, with a projected CAGR of 16.1% over the subsequent five years (Markets and Markets, 2023). This forecast closely aligns with predictions made by BCG and Blue Horizon in 2021 (BCG and Blue Horizon, 2021), suggesting that the cultivated meat market may reach US$1 billion by 2035. While the first startups have begun to scale up their operations, the CM market remains in its early stages. Globally, Singapore became the first country to allow the commercial sale of CM products in 2020 (Frezal et al., 2022; Sabelli, 2023). Following suit, the US has approved Upside Foods and Eat Just in 2022 and 2023 respectively, for the production of cultivated chicken and the use of the term "cell-cultivated chicken" on product labels (AgFunderNews, 2023). Although the EU has not yet approved the entry of cultivated meat products[16], the Netherlands has emerged as a pioneer in their development. It is home to the most successful European providers of cultivated meat – Mosa Meat and Meatable – and has become the first country in the EU to permit cultivated meat tasting, marking a significant milestone for the CM commercialization (Mosa Meat, 2023; Meatable, 2024). With Mosa Meat focusing on cultivated beef and Meatable on cultivated pork, they have been attempting to market their products in Singapore (FoodIngredientsFirst, 2022; Meatable, 2022). These products are primarily used in making dumplings and sausages tailored to Southeast Asian cuisine (Meatable, 2022; Meatable, 2023). Currently, companies tend to specialize in cultivating a single animal product. This applies not only to the producers mentioned above but also to companies like France's Vital Meat, which specializes in chicken, and Gourmey, known for its focus on foie gras (vegconomist, 2023). The following table presents a list of traditional meat production companies that are venturing into meat alternatives. Please note that this list does not represent all firms being active in this value chain, as there are many enabling companies in addition, e.g. with production know-how and machinery, suppliers of ingredients, processing aids or culture media.

[16] The first request for pre-market authorization in the EU-27 for lab-grown foie gras by the French company Gourmey in July 2024; see https://www.euractiv.com/section/agriculture-food/news/eu-gets-first-ever-request-to-authorise-sale-of-lab-grown-meat/

Table 9: Large European traditional meat production companies venturing into meat alternatives

Company	Country	Type of meat alternatives	Meat alternative products	Entry year
Hanegal	Denmark	Plant-based	Pâtés, vegetable curries, and dishes without chicken, tuna, and mackerel	2019
Danish Crown	Denmark	Plant-based	Meatballs, mince, burgers, nuggets, and a variety of sandwiches	2022
Jan Zandbergen Group	Netherlands	Plant-based	burgers, sausages, mince, schnitzels, meal components, chicken fillet	2019*
Vion	Netherlands	Plant-based	mince, burgers and schnitzels, sausages, chunks (chicken, beef and pork), bacon, and fish type products	2020
M-Food Group	Germany	Plant-based	mince products, fat substitutes for vegan salami products, and dough for vegan nuggets	
Ponnath	Germany	Plant-based	Sausages, burgers, schnitzels, plant-based cheese and spreads, burgers and nuggets, mince	2015
Rügenwalder Mühle	Germany	Plant-based	Liverwurst alternatives, nuggets, schnitzel, burgers and ground beef, and chili mince	2016
Tönnies Group	Germany	Plant-based	Sausages, smoked salmon alternatives, sandwiches, chicken alternatives, and fish sticks	2019
InFamily Foods Holding	Germany	Plant-based	Salami, bacon, and ham cubes	2020
InFamily Foods Holding	Germany	Cultivated	Not permitted in the EU market	2023
Richmond/Kerry Group	Irland and UK	Plant-based	Sausages, burgers, bacon, meatballs	2019
ABP Food Group	Irland	Plant-based	Beef, chicken, duck, lamb, beef mince, and meatballs	2019
Campofrío	Spain	Plant-based	Pizza, sausages and sandwiches, burgers, chicken strips, and nuggets	2017

Source: vegconomist (2024a), vegconomist (2024b), vegconomist (2024c), *Zandbergen (2024). Note: ranked alphabetically by country name and entry name.

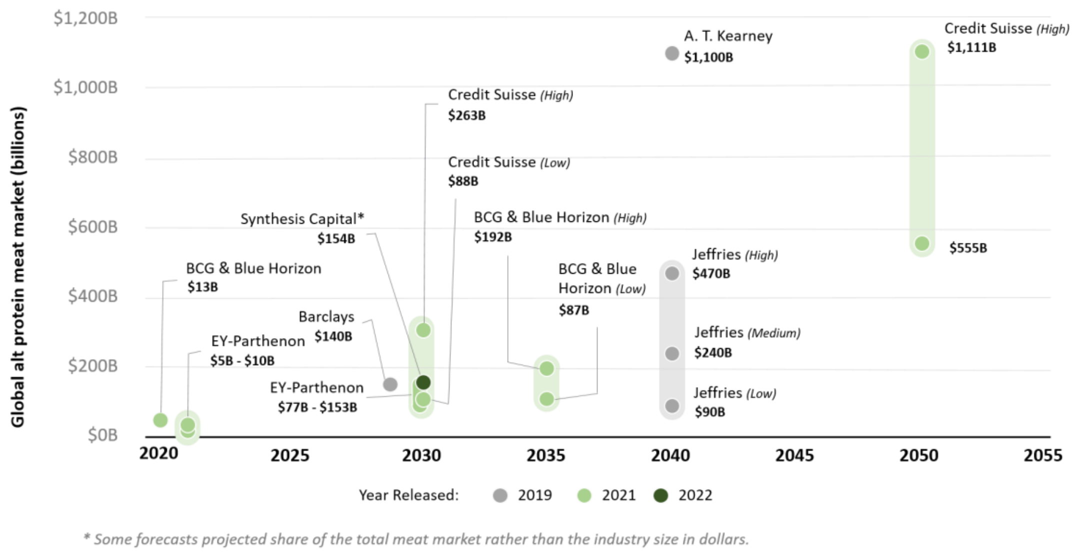
5.2.2 Market outlook

Market forecasts

Despite the relatively optimistic forecasts for both plant-based and cultivated meat in 2022 and 2023, retail sales of alternative meats in the US experienced a decline of 0.4% in 2022, contrasting with an 8% increase in sales of traditional meat during the same period (Von Koeller et al., 2023). Given that cultivated meat was not available in the US market in 2022, it is reasonable to infer that the decline in retail sales of alternative meat largely affected plant-based alternatives. According to the Good Food Institute (2024a), this decrease for plant-based alternatives was 12% in value from 2022 to 2023. Moreover, since 2022, Beyond Meat's stock price has witnessed its initial long-term decline rather than a short-term volatile one, a trend that has persisted into 2024. These trends reflect, in part, the diminishing demand for vegan food and heightened competition in the market (The Food Institute, 2023). The once lofty stock prices signify the high expectations of US investors, yet it appears that the market's readiness to embrace alternative meat has yet to materialize.

Various estimations for alternative meat (PBMA and cultivated meat) in the global market are summarized in Figure 28.

Figure 28: Total alternative meat industry forecasts by year released



Source: See graph

Drivers

The key driver from a policy point of view for alternative meat is the potential to meet the meat demand by significantly using less land and emissions. Those potentials are discussed in-depth in Section 5.3.2.

In addition, the EU is a net importer of proteins, importing an estimated 26% of the protein it consumes (European Parliament Think Tank, 2024). This raises concerns about protein self-sufficiency. Regarding protein imports, the EU imports not only food for human consumption (mainly fish and shellfish) but also feed for animal production (grains and grass, especially soybeans). In terms of feed protein sources, the EU is 77% self-sufficient overall, with the remainder reliant on imports (European Parliament Think Tank, 2024). However, war in Ukraine with Russia and Ukraine affects two key protein suppliers of the EU leading to higher global soybean prices. These prices have only recently returned to pre-war levels (Business Insider, 2024). This underscores the EU's dependence on third countries for feed or food, particularly when protein imports for animal feed are necessary. The use of edible proteins for animal feed is contentious due to its highly inefficient conversion process, where only 7-12% of plant protein is converted into animal protein (Berners-Lee et al., 2018). In this context, transitioning to plant-based proteins, such as alternative meat, could potentially reduce demand for feed protein in the EU, thereby enhancing protein self-sufficiency.

From a consumer and citizen point of view, sustainability is a key driver as well but keeping expectations to taste and dietaries.

Challenges

Plant-based and cultivated meats continue to face significant challenges, some of which are shared while others are unique to each. As two types of alternative meat products, they both encounter the following common challenges:

First, the challenge comes from the product itself. Plant-based meat alternatives and cultivated meat need to be competitive in terms of taste and texture compared to conventional meat to establish a presence in the market (Hüsing et al., 2023). While they are likely to offer health, environmental, and animal welfare benefits, ultimately, they are food products. If they fail to deliver on taste, convincing consumers to purchase them becomes difficult. Thus, there is a need to bolster research and development efforts within the food industry.

Secondly, plant-based meat alternatives and cultivated meat face price competitiveness issues compared to conventional meat (Hüsing et al., 2023; Von Koeller et al., 2023). In an inflationary environment where prices are on the rise, consumers may hesitate to pay a premium for alternative meat (Von Koeller et al., 2023). For instance, in Germany, common plant-based meat products are approximately 40 percent more expensive than their conventional counterparts (calculated based on unit value in 2023 provided by Statistisches Bundesamt (2024a). In contrast, alternative dairy products in Germany are priced similarly to traditional dairy products, or slightly higher (Siegrist et al, 2024). This partially explains why alternative dairy products lead the alternative protein category in terms of retail sales.

Furthermore, promoting plant-based meat alternatives and cultivated meat poses challenges in marketing. On one hand, consumers may lack literacy or awareness or have never tried such products. On the other hand, manufacturers may face strategic mismanagement in marketing efforts (Von Koeller et al., 2023). In the plant-based meat market, producers often use "vegan" and "vegetarian" labels on packaging to target consumers. However, this practice may alienate mainstream consumers. According to BCG, only about 20% of consumers in the fresh food market consider sustainability a top priority, while approximately 60% are concerned but not actively taking action, as they have other priorities (Von Koeller et al., 2023). Highlighting the "vegan" label creates a psychological barrier for mainstream consumers, leading them to believe the product is not for them. Hence, to promote plant-based meat alternatives more effectively, producers must broaden the dialogue beyond sustainability to focus on the needs that drive mainstream consumers' choices. Cultivated meat encounters a similar challenge in marketing strategy: will vegetarians purchase cultivated meat without concerns about animal welfare? Or are meat-eaters and other mainstream consumers more likely to become potential consumers of such products? Manufacturers must delve deeper into consumer psychology to address these questions. In summary, alternative meat producers must determine whether their products are seen as new vegetarian or vegan options favoured by vegetarians, or as initial steps for meat eaters transitioning. Preferences may differ across various countries and cultures. Alternatively, producers should consider whether it's beneficial for alternative meat to move beyond the vegetarian vs. meat dichotomy, focusing instead on cultivating a perception of health and taste to attract mainstream consumers.

Specifically for cultivated meat, significant challenges to legitimacy are evident, as depicted by the arguments outlined in Table 10. For potential marketing in the EU, CM producers will require product authorization at the EU level, necessitating thorough testing. Products involving genetic modification, such as those based on induced pluripotent stem cells, are likely to need to comply with EU regulations on genetically modified organisms, specifically Regulation (EC) No 1829/2003 and Directive 2001/18/EC (Post et al., 2020). Other CM products, such as those based on muscle stem cells, are expected to require approval by the European Commission under Regulation (EU) 2015/2283 on Novel Foods, with corresponding assessments conducted by the European Food Safety Authority (Froggatt and Wellesley, 2019). So far, the only application concerning a cultivated meat product has been submitted by the company Gourmey in 2024, but not yet approved in early 2025 (European Food Safety Authority, 2023; Monaco, 2025). Progress in EU regulations concerning cultivated meat might hinge on achieving consensus among EU countries. While the Netherlands, Spain, and Denmark are at the forefront, advocating for the legality of cultivated meat, Italy took a different stance by passing a proposal in 2023 that bans its production and commercialization for both human and animal consumption (Good Food Institute, 2023b; Sabelli, 2023). Legislators in France and Austria are contemplating similar actions (Good Food Institute, 2024b; vegconomist, 2023). This movement is driven not only by a collective commitment to addressing concerns regarding human health, animal welfare, and the environment but also by local protectionism for traditional meat production and related stakeholders (vegconomist, 2023). Such discrepancies in regulation inside EU may present a major barrier for European firms and creates uncertainties e.g. on investors side.

Moreover, for CM, scale-up is key challenge. The access to equipment and supplies, achieving desired texture, to optimize cell cultivation process and ensuring an animal-free process are key challenges companies face (Systemiq 2024; Kirsch et al., 2023).

Table 10: The legitimacy challenge: arguments for cultivated meat

1	CM cannot be considered "real" meat due to its production process. It is artificial and unnatural, as shown by terms such as "lab meat".
2	CM is a highly processed product, requiring unfamiliar production processes.
3	The energy-intensive production process contradicts the sustainability advantages of CM products.
4	CM is an inferior solution to plant-based diets with high proportions of fresh and not highly processed components.
5	CM confirms and solidifies the iconic status of meat and runs counter to efforts to reduce the importance of meat in dishes and diets and towards more plant-based diets.
6	CM runs counter to efforts to reduce meat consumption for health reasons, CM does not provide a bridging function to more plant-based diets.
7	It is uncertain whether CM will be accepted by larger consumer groups, or whether there is a lack of willingness to eat CM due to the perceived "unnaturalness".
8	Ethical concerns may relate to just availability and affordability. They may be hindered in case CM will be marketed as an exclusive luxury product.
9	The food and meat industry lacks the skills to develop and operate CM production processes.
10	Lack of positive perspectives and business models for livestock farmers and regions with a strong livestock production sector.
11	Developing, scaling-up, obtaining market approval and marketing CM requires large resources. The return on investment is uncertain due to technological challenges in product design and quality, the scale-up with first of its kind facilities, and uncertain consumer demand.
12	The requirements and procedures for risk and safety assessment of CM in the EU Novel Food regulation are just recently being update from January 2025 on and practicability still to be seen[17].

Source: Hüsing et al. (2023)

[17] https://european-biotechnology.com/latest-news/efsa-updates-guidelines-for-cultured-proteins-and-novel-food/

5.3 Economic, ecological, and social impacts: synthesis of literature

5.3.1 Economic impacts

Direct economic contribution

As outlined in the previous section, the alternative meat industry is still in an early stage and represents a small, dynamically growing niche.

The Good Food Institute lists companies that are working in the fields of alternative proteins.[18] This includes also firms that provide machinery, equipment or ingredients and in general diversified firms, for which alternative proteins is just one of their business areas among others. For 50 of these firms the database indicates a focus on meat, 8 of them active in cultivated meat, the others in plant-based or firms focused on precision fermentation.

According to scarce literature it is likely that this industry substitutes mostly value added and employment in traditional meat industry (see below). There are no indications, whether Germany is in particular strong or weak in alternative meat compared to its rather strong position in the meat industry, hence whether different import-export relations may occur in such a substitution path.

Structural changes

Structural changes in employment may occur due to shifts in value chains. The following stages of the meat industry's value chain may be significantly affected.

Plant farming: In 2018-2020, approximately 1.7 billion tonnes of cereals, protein meals, and processing by-products were used as animal feed (OECD & FAO, 2021). If there is a decline in meat demand, the demand for feed crops would also decrease (Frezal et al., 2022). Conversely, the demand for growing crops as feedstock for PBMAs or cultivated meat, respectively in agriculture would rise: PBMAs require plant-based proteins from crops such as peas, lupines, wheat, and beans (Fraunhofer Institute for Process Engineering and Packaging, 2024): Cultivated meat requires sugars as a cultivation medium from crops like barley, sugar beet, maize, peas, soybeans, and wheat (Frezal et al., 2022). This growing demand for alternative crops presents an opportunity for farmers, but the overall effect (including trade flows) is a priori uncertain.

Livestock farming: As the rise of alternative proteins is likely to lead to decreased demand for traditional meat in industrialized countries, this could lead to closure of small farms (Frezal et al., 2022). It is uncertain whether small-scale producers and large-scale producers can coexist in the emerging alternative meat (especially cultivated meat) system due to the complexity of the production technology (Stephens et al., 2018). Additionally, this transition could fundamentally change the nature of work in the livestock industry, shifting from roles based on farmers, farm workers, and meat processors to those based on chemists, cell biologists, engineers, and factory and warehouse workers (Heinrich-Böll-Stiftung, 2021). Traditional livestock workers may on the one hand benefit from better working conditions in alternative jobs, but will need technical training and skill upgrades to adapt to the new system.

Processors and distributors: The introduction of alternative meats is likely to reduce the number of people exposed to poor working conditions, which often exist in slaughterhouses of the traditional meat industry, e.g. the use of sharp objects, exposure to cold temperatures, excessive noise, repetitive tasks, and contact with potentially infectious substances and chemical products (Marzoque et al., 2021). However, as steps like animal slaughtering are not required for producing meat alternatives, job losses can be expected in slaughterhouses, abattoirs, the meatpacking industry, and

[18] https://gfi.org/resource/alternative-protein-company-database/

among small processors and distributors, such as butchers. It has to be seen whether those low-skilled workers might find alternative employment opportunities in other activities related to alternative meat processing, such as packaging and distribution in the plant and cultivated meat chain (Morais-Da-Silva et al., 2022). As some global meat processors and food companies have entered the alternative protein market by adding alternative protein businesses or investing in emerging SMEs focused on alternative meat, they may be able to mitigate potential job losses through internal employment restructuring (Frezal et al., 2022).

Prices

While the price will be decisive for the adoption of alternative meat (see Section 5.2), also indirect economic effects may occur via higher (or lower) purchasing power for other products and services and may lead to higher (or lower) growth. Moreover, structural effects via different cost structures are possible.

Currently PBMA have higher production costs than meats, as for meat decades of concentration and intensification of livestock production and advances in farming, slaughtering and meat processing technology have increased the cost efficiency. Various estimations about prices have been made, results depending highly on the country, chosen meat alternative, unit of analysis (e.g., burger patty, 100g pure meat), and time of analysis (as prices are quite fluctuating). The Good Food Institute estimated an average premium of 43% for 2022 (without clear geographical location) (Good Food Institute, 2023c), while ProVeg[19] estimates a drop of premia in Germany from 53% in 2021 to 25% in 2022 (ProVeg International, 2024). As mentioned in Section 5.2, calculations based on unit value in 2023 provided by Statistisches Bundesamt (2024a) are that PBMAs are approximately 40% more expensive than their conventional meat counterparts.

However, several reports (e.g., Good Food Institute, 2023c; BCG & Blue Horizon, 2021) are optimistic that cost competitiveness may be achieved in the future, as the plant inputs for PBMA are relatively cheap and in the future R&D costs are recouped, manufacturing operations achieve economies of scale, and raw material varieties and prices are optimized (Frezal et al., 2022).

Table 11: Cost components of plant-based meat

Type of costs	Share	Outlook
Channel costs and margins (e.g., retailer margins and fees, manufacturer margins)	20%	Per-unit costs can come down significantly.
Logistics (e.g., transportation and distribution costs)	5%	Per-unit costs can come down moderately.
Production and packaging	20%	Per-unit costs can come down significantly.
Materials (e.g., ingredients)	20%	Per-unit costs can come down significantly.
Selling, general and administrative expenses (SG&A)	20%	Per-unit costs can come down significantly.
R&D (research and development)	15%	Per-unit costs can come down significantly

Source: Good Food Institute (2023c)

There is hardly any information available on cost structures for plant-based meat alternatives, most likely as costs may significantly differ between the various products with different proteins used.

[19] https://vegconomist.com/retail-e-commerce/study-reveals-price-convergence-of-animal-and-plant-products-in-germany/

The following table summarizes estimations of Good Food Institute (2023c) shares of costs and assumptions for further development, while highlighting that the actual cost are highly depending on the company and stage of scale-up. Potential for cost decreases is e.g. seen by agronomic yield improvement (both overall crop yields and protein content), shared supply chains, process & facility scaling, low-cost extraction or by-product valorisation (oil, starch, fibre, extracts).

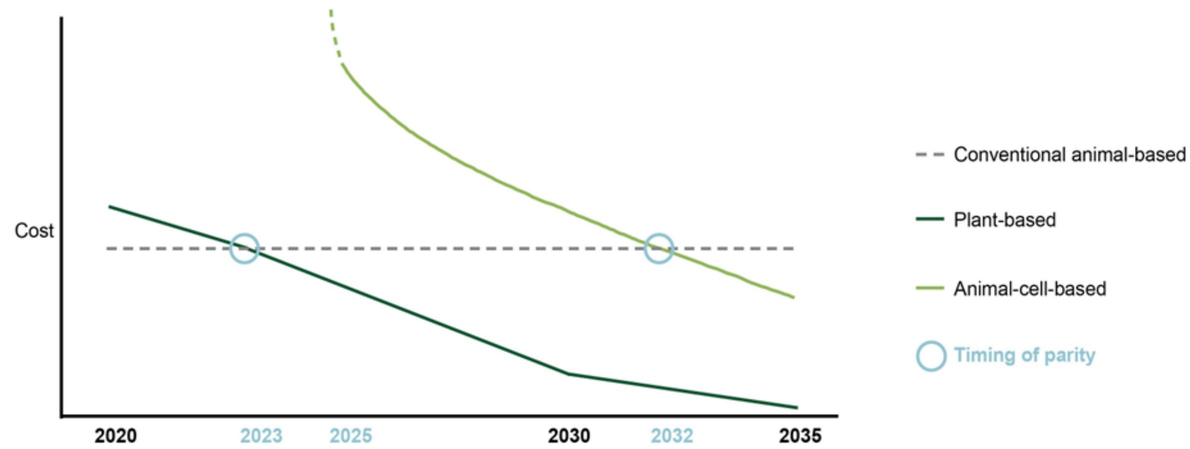
CM is currently much more expensive, because production techniques are not optimized and stabilized. Especially the cost of the growth medium is very high and estimated to account for 55% to 95% of the marginal cost of the product (Good Food Institute, 2020).

There have been a number of recent studies that perform a techno-economic analysis in the case of cultivated meat (Pathirana, 2024; Sinke et al., 2023; Specht, 2020; Sinke, 2021). Unsurprisingly, the studies differ significantly in cost estimates by several orders of magnitude. The estimations depend highly on the advances/efficiency in large-scale production of growth factors as an additive to the nutrient medium, in particular the costs of the growth medium However, all available studies consider that important cost reduction could be achieved in coming years, mainly through reductions in the cost of the growth medium which is the main driver of cost for cultivated meat. Some studies are optimistic that price parity may be reached in the forthcoming years.

Compared to traditional meat, CM production is capital intensive even in scenarios of significant production cost reduction. This is reflected in high investment costs and high capital expenditures per kg CM produced (~30% of costs), which are estimated. Moreover, cultivated meat production is likely to be rather work intensive, with significant share of labour cost (20-25%) as well as the growth medium (30%) needed for cultivation (Sinke, 2021; Sinke et al., 2023).

To conclude there are expectations of future price competitiveness but large uncertainties. An optimistic scenario is provided by Blue Horizon and BCG who provide forecasts when each alternative protein category will reach cost parity with conventional meat, emphasizing that each alternative protein production platform is currently at a different stage (BCG and Blue Horizon, 2021) Figure 29. Accordingly, PBMA were expected to reach cost parity already in 2023 while animal-cell based proteins will achieve parity only by 2032.

Figure 29: Relative timing of cost parity for alternative proteins with realistic taste and texture"



Source: Expert interviews; industry reports; Blud Horizon and BCG analysis
Illustrative data for US and EU; variations by proeuct group and geographic area are omitted for clarity.

Source: BCG and Blue Horizon (2021)

5.3.2 Ecological impacts

The potential environmental benefits of meat alternatives are in the centre of discussion. Livestock production contributes significantly to GHG emission and land use. Agriculture currently uses one third of the available land globally. Livestock production accounts for around 77% of all agricultural land (if feed production is included, while cropland occupies the remaining 23% (United Nations Environment Programme, 2023)[20]. Yet livestock provide less than 20% of calories humans get from food (European Parliament Think Tank, 2024). In a similar vein, greenhouse-gas emissions from livestock productions account for nearly 15% of the global total, a fraction that is expected to increase in the coming decades. In consequence, sustainable alternatives are urgently needed.

However, the assessment of the potential effects of meat alternatives are challenging for various reasons.

- All assessments have high uncertainty, as they have to rely on modelling and prospective assumptions regarding the large-scale production facilities (Rasmussen et al., 2024). In particular, studies on the environmental impacts of cultivated meat are only indicative, due to the early stage of the technology development. There are many challenges that need to be overcome before large-scale production is possible, such as development of animal-free culture medium, large-scale bioreactors and suitable cell lines for cell culturing. Hence, any environmental benefits can only be realized if the technologies can be scaled up to feasible commercial level production.
- For cultivated meat production processes, the impacts vary highly depending on the type of cells, the culture medium and the bioreactors used. Similar in the case of PBMA the concrete end product, way of processing as well as legume used may have a key impact on the results.
- The selection of type of meat that it is replaced, has a high impact on the results, as e.g. poultry requires much less land than beef.
- A key question are the consequences of land use changes. One impact could be that land-use requirements lead to reduced deforestation rates or even reforestation, especially if forests were converted into soybean production areas to produce livestock feed, leading to desired environmental impacts. Another impact could be that extensive pasture lands previously used for livestock grazing are converted to intensive crop production. In this case, environmental impacts would be undesired and negative. However, the mostly used attributional LCA does not account for these consequences of land use changes.
- Product-based assessments do not capture different by-products of livestock systems, e.g. milk and eggs next to meat for livestock production. Therefore, the environmental consequences of substituting meat can be understood only when considering the impacts of alternative ways of producing the by-products of livestock production. This can be done by expanding the system to consider the whole production systems and not only the main products. For examples, the assessment of substituting beef by PBMA or cultivated meat should include an assessment of the alternative ways of producing milk, leather, pet food, fertilizers, biogas and chemicals that are produced as the by-products of beef meat production.

Hence, the existing sustainability assessments have inherent limitations. However, overall, they confirm that meat alternatives meat use resources directly for human nutrition, without cycling them through animals, and thus require significantly less land. And alternative meat has significantly smaller GHG footprints compared to beef and pork, as e.g. they do not require raising methane-emitting livestock as for beef and growing crops for feed.

[20] However, a significant percentage of this land cannot be used for arable crops.

As an indication of the potential range of effects, Table 12 shows some results collected by the Good Food Institute (2023a). They show high potential for the reduction of GHG emissions, land use, and air pollution for PBMA and cultivated meat.

Table 12: Comparative life cycle assessments for meat alternatives

Comparative Life Cycle Assessments*

Producing this alternative protein	instead of this conventional meat	reduces this environmental impact category by this much		
		GHG EMISSIONS	LAND USE	AIR POLLUTION (PM)
Impossible Burger[I]	Beef burger patty	89%	96%	–
Beyond Burger[II]	Beef burger patty	90%	97%	–
Quorn Fillet[III]	Chicken breast	75%	78%	–
Morningstar Original Chik Patties[IV]	Chicken sausage patty	46%	84%	69%
Plant-based burger (soy protein)[V]	Beef burger patty	98%	87%	99%
	Chicken burger patty	90%	82%	90%
	Pork burger patty	90%	85%	90%
Plant-based burger (soy)[VI]	Beef burger patties	82%	84%	95%
Plant-based burger (pea)[VI]		84%	64%	91%
Fermentation-based burger (mycoprotein)[VI]		82%	69%	91%
Cultivated beef[VII]	Conventional beef	92%	90%	94%
Cultivated chicken[VII]	Conventional chicken	+3%	64%	20%
Cultivated pork[VII]	Conventional pork	44%	67%	42%

Sources: I. Khan, et al. (2019); II. Heller, et al. (2023); III. Kazer, et al. (2021); IV. Dettling, et al. (2016); V. Saerens, et al. (2021); VI. Smetana, et al. (2021); VII. Sinke, et al. (2023).**

Source: Good Food Institute (2023a)

In the following, the results from table 12 but also additional ones are discussed in more detail:

PBMA comprises a large range of products, each with specific characteristics and production contexts that will determine their impacts (United Nations Environment Programme, 2023). Smetana et al. (2023) conclude that PBMA have twice as low GHG emissions (4,963 kgCO_2eq.) as animal-based foods (9,923 kgCO_2eq.) per kg end product. According to the LCA meta-study by Shanmugam (Shanmugam et al., 2023) the median climate impact of final PBMAs was estimated even only at 1.7 billion kgCO_2eq with a more than fourfold variation in impact among the products assessed. They find energy use in the extraction of protein and the type of raw material and associated agriculture activities as major areas of improved climate performance.

On a protein basis, Smetana et al. (2023) conclude that animal-based proteins have a considerably higher GHG emission than proteins incorporated in plant-based meat substitutes: farmed fish (34%); poultry meat (43%), pig meat (63%), farmed crustaceans (72%), beef from dairy herds (87%), and beef from beef herds (93%). Hence, the environmental impact of the meat substitutes strongly depends on the type of meat to be substituted.

The United Nations Environment Programme (2023) review of life cycle assessment (LCAs) suggest that compared to conventional beef, PBMA show lower values with 67–89 per cent in GHG emissions. In addition, they could use 30–50 per cent less energy whilst offering reductions of 86–97 per cent in land use[21].

[21] The water footprints for plant-based alternatives are highly variable and highly dependent on their main sources of protein and the manner of processing and the substitute (Fresán et al. 2019, Potter et al. 2020). Overall, UBA (2023) concludes that plant-based meat substitutes therefore have advantages over conventional meat.

However, several studies have pointed out that legumes, vegetables, nuts and grains, with minimal processing exceed GHG emission reductions of plant-based substitutes (Clune et al., 2017; Poore and Nemecek, 2018). According to Smetana et al. (2023), the addition of minor components like spices and preservatives usually add 13–26% to the resource demand and therefore increases the environmental impact of PBMAs. Hence, a higher level of processing and the inclusion of a longer list of components usually increase the environmental footprint of PBMAs.

Still the impacts on a product basis of PBMA may have significant macro-impacts. According to a scenario exercise from Kozicka et al. (2023) a rise to half the global protein market, including dairy, would mitigate 2.1 gigatons of carbon dioxide equivalent annually, and agriculture and land-use GHG emissions would decline by 31% by 2050 instead of increasing.

Concerning CM, the analysis of Sinke (2021) and a respective update of the authors in Sinke et al. 2023 got high attention as key input data is derived by information and expectations from cultivated meat firms. Sinke et al. (2023) estimate emissions associated with CM in 2030, assuming that the production process can use food-grade ingredients and will reach commercial scale sometime in the next decade. That study put the potential climate impact at between three and 14 kilograms of carbon dioxide per kilogram of cultivated meat depending on if renewables are used to power the facility and on what ingredients are in the media used to grow the cells. Some studies are even more optimistic. The review of seven LCA for CM (including the one from Sinke et al. (2023) by United Nations Environment Programme (2023) reports an even lower value of 2.3 kg CO_2eq per kg of meat, while GHG emission from produced beef of an estimated 26.2 to 99 kg CO_2eq per kg of meat). For cultivated meat all of the reviewed LCAs foresee drastic reductions compared to conventional meat production in land use of 97–99% per kg for beef, 60–99% per kg for pork and 43–98% per kg for chicken. Tuomisto (2022) concluded as well that cultivated meat have lower carbon footprint and land use but require more energy than livestock products. Smetana et al. (2023) point out that using low emission energy sources in cultivated meat production is necessary to achieve lower emissions compared to pork and poultry. The energy use as well as the overall environmental impact depend largely on the bioreactor energy use as well as the production of the culture medium ingredients (Sinke et al., 2023; Mattick et al., 2015).

Some critical assessments question the chosen assumptions regarding the growth media. A team of the University of California (Risner et al., 2023) estimates the climate impacts of cultivated meat assuming current production techniques which rely on materials and techniques borrowed from the biopharmaceutical industry. They show that under the current production scenario, cultivated meat would be produced with processes and materials similar to those used in the biopharmaceutical industry. This could result in GHG emissions of 250 to 1,000 kg per kilogram of meat, which is much higher than the emissions associated with beef. This assessment points out that still significant progress is needed, and Goodwin et al. (2024) conclude in a comparison between techno-economic assessment studies and technical research in cultivated meat, that needed large scale production methods (stirred tank bioreactors, suspension-tolerant, continuously available cell lines) are only to a limited extent in the focus of current research.

To conclude, the reviewed meta-assessments are rather in line with the data shown in Table 12. They and indicate at least significant future sustainability potential of PMBA and cultivated meat. However, still many question to harmonize LCAs, to transfer LCA insights and very high reliance on future assumptions of scaled-up production persist. In addition, a broad sustainability perspective is needed to better understand the role of PBMAs in the transition towards more sustainable diets (Shanmugam et al., 2023).

5.3.3 Other impacts

Animal welfare

In 2023, global meat production reached 371 million tons, marking a 425.72% increase from 1961 (FAO, 2023; FAO, 2024). Regardless of whether the farm is an industrialized large-scale operation or a small-scale organic farm, animal welfare issues such as limited space and painful body modifications are prevalent (Santo et al., 2020). In this case, the widespread adoption of meat substitutes could significantly reduce the reliance on raising and slaughtering livestock for meat production (Santo et al., 2020).

However, the production of cultivated meat may still face animal welfare issues due to its reliance on animal-origin materials. The process of producing cultivated meat requires animal cells, and there are two main techniques: The first technique requires cells from only one animal but involves genetic modification and is still in its early stages of development (Santo et al., 2020). The second technique necessitates a constant supply of animals to obtain adult muscle stem cells from biopsies, which can be taken from live or deceased animals (Santo et al., 2020). Since these animals must be biopsied regularly to provide muscle stem cells, their living conditions should be carefully evaluated (Chriki et al., 2022). Furthermore, due to the cost and current maturity of the technology, cell and tissue culture media often require inputs from animal sources (Santo et al., 2020; Chriki et al., 2022). This includes fetal bovine serum, which is extracted from the blood of live bovine fetuses after the mother cow has been slaughtered for meat processing. Consequently, the production of cultivated meat would still rely on the slaughter of animals. For cost and animal welfare reasons, intensive research efforts are taken to replace fetal bovine serum by functionally equivalent substances from non-animal sources.

Public health

According to the OECD, popular plant-based products mimicking beef have a similar protein value, are equally rich in vitamins, and have a comparable amount of fat as conventional beef (Frezal, 2022). However, there are concerns about the health implications of plant-based alternatives due to their high degree of processing, which introduces various additives. Excessive consumption of processed foods has been associated with an increased risk of diet-related diseases (Santos et al., 2020). Data also suggest that plant-based products mimicking beef contain five times more sodium than regular beef – a plant-based beef burger contains about 10% of the recommended daily amount (Frezal, 2022). While it has been argued that not all processed foods are unhealthy, it remains unclear which aspects of food processing and formulation are primarily associated with diet-related diseases (Tso & Forde, 2021). Therefore, more research is needed on the nutritional and health effects of replacing animal foods with plant-based alternatives, considering factors such as raw materials, processing, and preservation.

Regarding cultivated meat, comprehensive baseline nutritional data are not yet publicly available (Frezal et al., 2022). However, theoretically, since the molecular structure of cultivated meat closely resembles that of conventional meat, it has been assumed that it could be an almost perfect substitute in terms of nutritional value (Food Safety News, 2017). However, also meat biomass derived from cell cultures require processing to achieve meat-like organoleptic properties. Little is publicly known about the exact composition and their nutritional value of such products. Because lab-cultured meat is produced in an aseptic environment, the risk of foodborne pathogens such as Salmonella and E. coli is reduced (Food Safety News, 2017).

Overall, while both plant-based and cultivated meat offer promising alternatives to conventional meat, their long-term health impacts require further investigation. Both product types only lead to the desired impacts if they really replace animal-derived meat to a certain extent, so that per capitameat consumption is reduced. This requires further research how to design food environments to achieve the intended outcomes and impacts (Zaleskiewicz et al., 2024).

5.4 Conclusions

Meat alternatives are highly promising innovations in the bio-based sector due to their potential to reduce land use and GHG emissions, and to contribute to healthier diets. There are high expectations of market diffusion in the forthcoming decades.

However, there are significant differences in market forecasts regarding timing and level of substitution rates of traditional meat. As a relative advantage, alternative meat has less price disadvantages than other bio-based innovations. While price "equalness" is not met yet, here meat alternatives have the potential to reach it, as the substitutes require traditional processing steps, but can avoid steps with livestock production.

Germany seems to be in a rather promising position, with some traditional meat companies entering the market for PBMA and some researchers and companies being active in the field of cultivated meat. However, regarding cultivated meat European food regulations for novel food are considered as a significant barrier to market entry due to their high administrative burdens and lengthy regulatory processes. However, the European Food Safety Authority (EFSA) is active in developing guidance for applicants and is in exchange with other regulatory authorities (e.g., Food and Drug Administration (FDA) in the U.S.A., Singapore). Moreover, consumer acceptance is uncertain for cultivated meat.

Regarding impact, the emerging literature on sustainability impacts highlights a positive effect on land use and GHG emissions, which could lead to significant macro-level impacts under scenarios of significant substitution rates. However, such an assessment of meat alternatives still faces many challenges, including boundary setting, type of product, processes, and substitutes considered, the lack of data in this early development phase, and the need to account for the whole protein system. This is particularly relevant for cultivated meat, which is still in the R&D phase, still requiring scale-up to industrial mass production, and not yet on the European market. The potential assessments on efficiency and sustainability largely depends on assumption of mass production patterns, which still must be developed.

On the economic data side, alternative meat has been taken up with an own explicit product code in relevant statistics, which helps to analyse production development over time. Information on industry is less clear: while there are firm inventories, especially the role of larger firms is not easy to capture. Moreover, the net economic and ecological impacts of alternative meat largely depend on structural effects: First, it is unclear whether the meat substitution will actually lead to a reduced demand for land use for animal feed and meat production as the rising world population and demand in merging countries may counteract this. Moreover, even if meat demand falls, the question is whether it would lead to reforestation or more croplands will significantly impact GHG emissions. Should cultivated meat achieve a mass production status in the more distant future, this would imply a significant change in value chain structures. The consequences for farmers will determine the economic impact, which may differ significantly across the globe.

However, the net impact is a result of a larger industry transition. Here, especially structural effects impact the entire value chains.

While first models have been developed to analyse such effects, they mostly cover only few dimensions of the potential impact, and more integrated assessments are still to come. Of high importance will be here the consideration of full implications on protein markets and livestock management as well further exploration of developments of land use changes.

A.1.1 Potential development paths and structural effects

Based on the case study delineations for a scenario wedge in a GLORIA-based MRIO model were developed. For the results of the modelling – one of several scenario wedges – please see Lutz et al. (2024).

The substitution of meat by alternatives is expected to have significant structural impact from livestock farming which would significantly change towards either more plant farming or industrial production (cultivated meat). However, projections on value chains and market volumes are highly uncertain, as they depend largely on presumed technological progress, in particular for cultivated meat, as well as consumer behaviour and market regulation.

In order to estimate the potential range of impacts, we assume a scenario of a significant uptake of meat alternatives, including a successful market entry of cultivated meat. We take estimates in the middle range of existing studies, which still would indicate a very significant take up of meat alternatives. Therefore, we take the moderate scenarios on market projections and considerations of an OECD scenario (Frezal et al., 2022) and assume a decrease of meat consumption about 10% for 2030, which is substituted by plant-based meat (90%), but also to some extent by cultivated meat (10%). For 2040, a market share of 25% of alternative meat, with 60% presented by PBMAs and 40% cultivated meat is assumed, which is in between of the bandwidth of estimations. It is assumed that the projected decrease of meat productions takes place proportionally for beef, pork, poultry and other meat products.

With the underlying assumption of price parity of meat and its substitutes – which is very congruent/plausible in such scenario of significant diffusion - cost structures are of significant importance to model the value chains within an input-output based model. There have been a number of recent studies that perform techno-economic analysis in the case of cultivated meat (Pathirana, 2024; Sinke et al., 2023; Specht, 2020; Sinke, 2021). Unsurprisingly, the studies differ significantly in cost estimates, and these depend highly on the advances/efficiency of large-scale recombinant protein production. As for broad diffusion, a cost competitiveness of cultivated meat has to be reached to achieve cost competitiveness and price parity with conventional meat, costs for cultivated meat will have to be reduced enormously. For our model, we assume optimistic estimations. Compared to traditional meat, CM production is capital intensive. This is reflected in high investment costs and high capital expenditures per kg CM produced: a share of ~30% of costs is estimated. Moreover, cultivated meat production is likely to be rather labour intensive, with significant share of labour cost (20-25%) as well as the growth medium (30%) needed for cultivation (Sinke, 2021; Sinke et al., 2023). By contrast, there is hardly any information publicly available on costs structure for plant-based meat alternatives, most likely as costs may significantly differ between the various products with different proteins used. An analysis by the Good Food Institute (Good Food Institute, 2023c) reveals that costs are rather equally distributed across the categories "Channel costs and margins (e.g., retailer margins and fees, manufacturer margins)", "Production and Packaging", "Ingredients", "Sell, "General administrative expenses, "R&D". For the future, potential for cost reduction is seen in various categories. Therefore, achieving cost competitiveness compared of traditional meat seems realistic (Good Food Institute, 2023c).

Based on these estimations, the input structures of the four meat categories beef, pork, poultry, and other meat products are modified by taking into account the share of substituted values and the alternative input structure for these shares. In other words, we keep the sector meat production in its size but consider that the above-mentioned share is presented by alternative meat, which leads to different average input structures. Hence, while feed and livestock production and partly transport is declining, the input of (bio-)chemicals for cultivated meat production, plant feedstock, capital, partly R&D costs are increasing. The model would have to be adjusted with some effort to take capital costs into account. Therefore, they were not considered.

Table 13: Assumptions for the wedge alternative meat

Product group as input in	Product group	Country	Change compared to 2021
Leguminous crops and oil seeds	Meat production (Beef, pork, poultry, other meat products)	DE	Increase of input co-efficient to 0.015
Vegetables, roots, tubers	Meat production (Beef, pork, poultry, other meat products)	DE	Increase of input co-efficient to 0.015
Basic chemicals, pharma-ceuticals	Meat production (Beef, pork, poultry, other meat products)	DE	Increase of input co-efficient to 0.015 after 2030
Meat (Raising of cattle, swine, poultry, animals n.e.c., production of beef, pork, poultry, other meat products)	Meat production (Beef, pork, poultry, other meat products)	DE	Decrease to 90% by 2030, to 75% by 2050
Food products (Cereal products, vegetable prod-ucts, fruit products, food products and feed, sugar refining and cacao)	Meat production (Beef, pork, poultry, other meat products)	DE	Decrease to 95% by 2030, 85% by 2050
Transport (Wholesale and retail trade, road, rail, pipe-line, water, air, services to transport)	Meat production (Beef, pork, poultry, other meat products)	DE	Decrease to 95% by 2030, 87,5% by 2050
Professional, scientific and technical services	Meat production (Beef, pork, poultry, other meat products)	DE	Increase to 130%

Source: Fraunhofer ISI

The results of the modelling – one of several scenario wedges – are presented in Lutz et al. (2024). The main findings are that biotic material inputs and related GHG emissions could be slightly lower than in the reference. However, the effect is significantly lower than in a scenario, which assumes an implantation of the recommendations of Deutsche Gesellschaft für Ernährung e. V. (DGE) on dietary change.

6 Conclusion

The assessment of the case studies highlights the transformative potential of the bioeconomy and its capacity to address pressing global challenges such as resource depletion, climate change, human health and food security. By examining specific technological fields, the study provides insights into the innovation pathways and structural challenges shaping the bioeconomy's development.

The four technological fields assessed – biopharmaceuticals, bio-based surfactants, alternative meat, and AI in regenerative agriculture – reveal distinct characteristics. Biopharmaceuticals stand out with the highest diffusion of biotechnology and a relatively mature market presence. In contrast, innovations in the other fields occupy niche markets, some of which remain very small to date, and possibly also in the foreseeable future. Among these, alternative meat demonstrates the greatest potential for achieving significant direct economic impact in the future. Each of these fields follows distinct innovation paths, encompassing technologies that are closer to market readiness and those requiring substantial investment and further development.

Environmental sustainability serves as a common driving force across most fields, guiding efforts to reduce environmental impact and improve resource efficiency. For biopharmaceuticals, sustainability is not the main driver but also here getting higher attention. However, significant challenges remain, including high costs, limited technological maturity, and gaps in regulatory frameworks and market standards. These challenges introduce significant uncertainty, particularly for technologies that depend on value chain integration and policy support for their successful commercialization.

While environmental sustainability and technological progress offer substantial potential, the current limited market diffusion of these innovations constrains their direct economic impact. With the exception of biopharmaceuticals, the actual direct economic impact remains rather modest. Understanding the mechanisms through which these technologies influence markets and industries is crucial for assessing their long-term potential.

The markets specific for the analysed technological fields are expected to grow, but in most cases, growth will substitute to a significant extent existing products and processes. Hence, the economic impact will largely depend on structural effects via new value chains or shifts in consumption patterns. These are influenced by changes in income levels (higher/less or lower), prices as well as the role of Germany as a developer and producer of those bio-based innovations. In addition, there may be strong signalling effects to other bio-based segments, if these innovations achieve significant market penetration and impact (e.g. use of innovative methods for bio-based surfactants providing specific functionalities to products).

Building on the discussion of Germany's role in bio-based innovation, the case studies provide insights into its competitiveness and potential as a hub for further development, production, and employment. However, the findings suggest that the early-stage maturity of most technologies limits the ability to draw clear conclusions about which countries might secure a leading position. In the more advanced field of biopharmaceuticals, Germany demonstrates a strong position in development and production but does not currently lead on a global scale.

These market dynamics are further reflected in the sustainability potential and challenges observed across specific technological fields. In most case studies, sustainability emerges as a key driver, with biopharmaceuticals receiving significantly more attention in this regard than in the past. Among the fields, alternative meat demonstrates the most notable potential impact, particularly in reducing intensive land use. By contrast, raw material substitution plays a less significant role in other fields. A bit different is the case of AI in regenerative agriculture, with the latter having a clear potential for sustainable agriculture. However, the effect of AI is difficult to identify. And this case highlights that it matters, which technology options are used and whether efficiency gains are in focus, potentially leading also to higher production and consumption of products, or whether the new innovations are strongly integrated into a systemic approach to approach.

Overall, bio-based products and processes across all analysed technological fields hold considerable potential for positive contributions to sustainability. However, a lack of comparable assessments and reliance on future technological assumptions often limit the ability to draw definitive conclusions.

Regarding the measurement and monitoring of innovations the following observation and conclusions can be drawn: Individual approaches were applied in the case studies (Table 14), mostly due to data availability and because straightforward assessments of publications, patents, and meta-market analysis (partly replicated, partly updated here) were already presented in the Deliverable 1.5.1 (Wydra et al., 2023). From those additional assessments some conclusions can be drawn for future data collection and analysis in terms of more detailed or more continuous assessments and/or regarding replication for other bio-based segments. As the last column in Table 14 shows these potentials for further or continuous analyses differ between the case studies as rather different quantitative approaches with different analytical goals were chosen (survey, indicators, modelling). Overall, there are possibilities to extend the quantitative assessment of the bioeconomy at least for relevant sub-fields. The main insights form the four cases studies are the following:

For biopharmaceuticals, the analysis focused mainly on the relatively rich availability of "bio"-related indicators, which are partially non-replicable in other cases, as the regulatory frameworks allow for straightforward identification of a limited number of "bio-"products that can also be related to market assessments. The example of bio-based surfactants showed that, with field-specific expertise, it is possible to identify certain steps in the value chain (e.g., R&D and production) of firms. However, many firms operate in multiple chemical fields, not exclusively in bio-surfactants, making it difficult to isolate the contribution of bio-surfactants. The firm data in databases pertains to all these activities, and the specific contribution of bio-surfactants cannot be identified. Moreover, the transferability of this manual approach to identifying firms in larger segments is limited. In the case of AI in regenerative agriculture, an online survey appears to be the only feasible option to obtain relevant data. As a continuous assessment of the use of such technologies is needed, this may be only feasible through standardized surveys, similar to the Eurostat survey of ICT use in enterprises[22]. For alternative meat, the objective was to set a basis for modelling exercises, given the significant indirect impacts that are at least conceivable throughout the economy. Although the literature provides a solid foundation for estimating market diffusion and impact channels for this emerging topic, substantial uncertainties remain about future developments and inherent limitations in MRIO models to take investments fully into consideration. Nevertheless, this represents a promising example of how innovations can be more effectively integrated into modelling exercises.

Table 14 summarizes the approach taken, results obtained and the potential for extending/continuing data analysis or replication to other segments.

[22] https://ec.europa.eu/eurostat/cache/metadata/en/isoc_e_esms.htm

Table 14: Quantitative assessments in case studies

Title	Quantitative Assessment	Key results	Implications for future Data Analysis a) More in-depth Analysis b) Continuous assessment c) Replication to other segments
Artificial Intelligence (AI) in regenerative agriculture	Online expert survey of adoption and impacts of AI in regenerative agriculture	AI technologies are currently mostly used in experimental/pilot projects and small-scale implementations; main benefit is higher efficiency	a) Specification about AI-technologies in surveys recommendable b) Establishment or integration in standard survey is needed c) Survey concept transferable to other enabling technologies or total agriculture
Biopharma	Collection of existing indicators (e.g., biopharmaceutical pipeline, authorization, market sales, employment)	Germany has a strong pipeline with 672 biologics in clinical development; biopharmaceuticals account for more than half of the EU marketing authorisations	a) - b) Already regular assessment c) Limited transferability to other segments, as a limited number of identifiable products exist only in very few bio-based fields, usually those where registration is required (e.g. novel food/feed, pesticides)
Bio-based surfactants (2nd generation)	Identification of relevant firms in Crunchbase (via keywords, patent applicants in related databases, market studies) and characterization regarding country, year founded, employment	The US is leading in number of firms, primarily young SMEs, while German excels with large chemical firms entering this field	a) – b) Updates a bit laborious as manual checks for new entries and exists needed c) It is manually feasible for value chain stages in certain bio-based segments (e.g. biofuels, biolubricants, alternative meat)
Meat alternatives	Use of secondary official statistical data for alternative meat Derivation of key input data for scenario modelling for Germany with a time frame to 2040 based on literature assessment	Significant diffusion of alternative meat is possible with considerable structural effects of economic activities	a) Extension to more impact channels for alternative meat possible if it relates to structural effects and data is available b) A bit laborious, as updates of input data and modelling needed c) Extension to whole alternative proteins feasible

These quantitative approaches, while valuable, each address a specific field and are not easily combined into an integrated assessment. As such, they provide primarily exploratory information and can inform efforts toward more systematic evaluations of innovative fields.

Moreover, although it was anticipated from the beginning that only secondary data on ecological impact would be available, the information proved to be notably limited. The number of products or segments covered was constrained, and numerous methodological issues – such as boundary setting, assumptions about the future, and the scope of analysis – limit the comparability of existing studies and the general conclusions that can be drawn. This limitation may persist given the wide range of products and processes that the bioeconomy encompasses. However, greater harmonization and coherence in environmental assessment methodologies would enhance their utility.

Nevertheless, the case studies demonstrated the potential for further development and systematic use of quantitative information, which enriched the possibility of evidence-based assessment of these fields. They can be regarded as an important starting point for research in the future.

7 List of figures

8 List of tables

9 Bibliography

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