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A Value Chain Strategy for a Vital EU Bioeconomy

Unlocking the Potential of Biotech beyond Food Chains

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Technologies involving the responsible use of biological resources not only strengthen the innovativeness of Europe's industrial sector, but also contribute to multiple sustainability goals under the EU Green Deal. With the upcoming biotech and biomanufacturing initiative, the EU is asked to develop an updated strategy for a competitive industrial bioeconomy. This cepInput analyses the current situation and proposes key fields of action as part of a value-chain-focused approach.

Key results:

- The commercialization of innovative bio-based products in the EU faces significant general barriers, foremost insufficient access to venture capital and a lack of qualified workers. In addition, sustainability issues around feedstock extraction and the complexity of the product landscape hinder market uptake in some segments.
- In the field of biotech research, patenting activities by inventors from the EU27 have recently shown weaker momentum than those from China and the US. To maintain its position in the global technology race, the EU should seek to develop the key strengths of its most innovative regions: an abundance of scientific and engineering talent, an overall high level of education and a high degree of supra-regional research cooperation.
- Policy strategies for tackling obstacles to growth must adopt a value chain perspective. Three fields of policy action are of general importance: securing access to critical inputs, supporting the formation of competitive green markets and strengthening stakeholder cooperation along and beyond value chains. To implement support instruments in a consistent manner, continuous exchange with industry stakeholders, and binding quantitative targets for replacing fossil feedstock use are required.

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1 Background

Until now, European policy debates on sustainability goals circle around a very limited set of technology solutions: wind power, photovoltaics and their associated downstream technologies. While the fundamental importance of these energy sources for the EU's green transition is undeniable, the ambitiousness of the goals requires policy strategies to cover a broader horizon. Bio-based solutions, in particular, should be empowered to realize their full potential in manufacturing, beyond the traditional applications in food processing, furniture and textiles. They are not only capable of replacing fossil resources in some industry segments like basic chemicals, plastics and fuels, thereby contributing to a lower carbon footprint and a reduced dependence on fossil resource imports. They are also an important driver of product and process innovation, given their strong interlinkages with neighbouring technology fields such as nanotechnologies and medical engineering. Recently, the rapid leap in the development of messenger RNA vaccines at the beginning of the COVID-19 pandemic has demonstrated to the wider public the relevance of biotechnologies for fundamental welfare issues.

The upcoming EU initiative on biotechnologies and biomanufacturing represents an ideal opportunity for realigning policy priorities. To be successful, it needs to deal with a range of specific challenges. Technological complexity and the variety of process steps required to convert a biological feedstock into an industrial product render development and production extremely capital- and knowledge-intensive. This does not put Europe in an ideal starting position for the global biotech race of the future. For instance, the venture capital markets needed to turn research success into viable new business models are still comparatively underdeveloped in the EU. The supply of specialized skilled labour threatens to become even more constrained due to ongoing demographic change and the gap between academic training and practical requirements. Unresolved sustainability issues associated with biomass extraction contribute to uncertainty on the demand side, while the switch to second and third-generation feedstocks is in part still hampered by the dominance of scale economies. At the same time, the considerable regulatory complexity imposes development constraints and high administrative costs on biotech industries. Under the current state of affairs, Europe is in danger of squandering its growth potential in this key industrial segment of the future. This would not only constitute a further setback for securing industrial competitiveness but would also jeopardize multiple sustainability goals under the EU Green Deal.

Based on a detailed screening of the current production and innovation landscape, this cepInput develops a distinct value-chain-oriented policy agenda for strengthening the market uptake of biotech innovation and the competitiveness of bio-based manufacturing in the EU. It starts with an assessment of the current economic and societal relevance of the EU bioeconomy and its growth barriers, emphasizing the role of spatial agglomeration forces as a policy-relevant feature of bio-based industries. Then, by means of a comprehensive analysis of patent data, it identifies trends and patterns in the EU's innovation performance in biotechnologies, both on a global scale and at regional level. It goes on to examine the toolsets of previous EU development strategies for the bioeconomy and their interplay with recent Green Deal legislation. Finally, the paper translates the results into three key fields of policy action, along with concrete instruments for addressing identified obstacles across all stages of bio-based value chains.

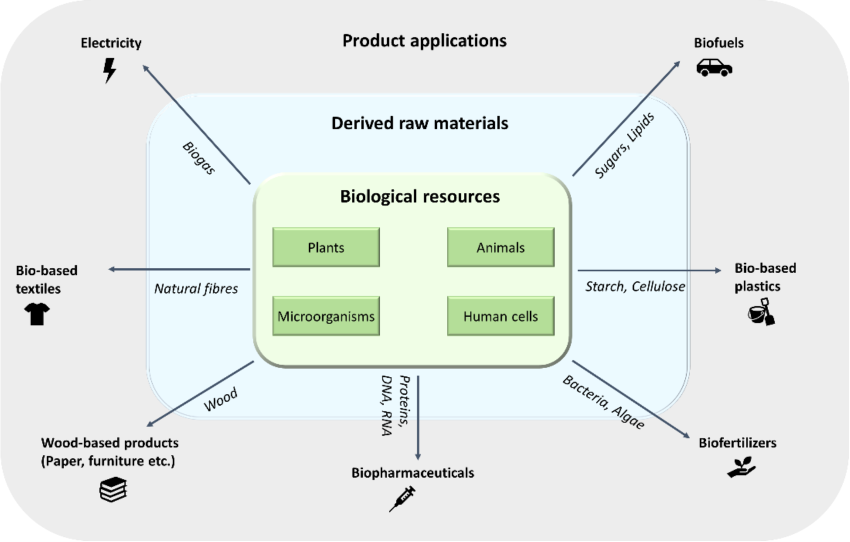
2 Characteristics of the EU bioeconomy

2.1 Delineation

In general, the term "bioeconomy" has been associated with a range of quite different meanings. The exact sense depends on the national or regional context and tends to vary over time with the state of technological progress and the emergence of new products and services. The definition preferred by EU policymakers has also been subject to slight modifications, as a consequence of shifting policy priorities. In its most recent review of the EU bioeconomy strategy in 2022, the European Commission defines the bioeconomy as encompassing "all sectors and associated services and investments that produce, use, process, distribute or consume biological resources, including ecosystem services".[1] In this respect, biological resources are not limited to animals and plants, but include microorganisms and cell materials as well as derived biomass and organic waste. The definition makes clear that relevant activities are not restricted to the physical handling of these resources, but also involve accompanying services (e.g. trade, research) and the financing of associated businesses. The Commission thus takes a value chain perspective on the bioeconomy, considering all steps of biomass processing and their related service inputs to be an integral part of the EU bioeconomy.

In what follows, we adopt this holistic definition of a bioeconomy, so as to remain consistent with EU data sources. Its broad scope sheds light on the wide range of bio-based product applications developed in the recent past. Figure 1 provides a (non-exhaustive) overview of current production pathways for bio-based resources. Beyond their traditional uses in segments like food, paper and textile production, biological resources have been involved for quite some time in the chemical and pharmaceutical domains. In this regard, they not only provide the basis for health and life enhancing product innovation (e.g. vaccines) but are also able to replace minerals and fossil fuels in established process chains.

Figure 1: Utilization pathways of biological resources in (non-food) manufacturing



Source: own illustration

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[1] European Commission (2022a). EU Bioeconomy Strategy Progress Report - European Bioeconomy policy: stocktaking and future developments. Report from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2022) 283 final.

2.2 Strategic relevance

The growing diversity of the bioeconomy enhances its macroeconomic significance. However, the bioeconomy's cross-sectoral nature complicates the assessment its significance using typical key figures such as value added and employment. The size of a bio-based sub-segment within sectors like the chemical industry cannot be calculated directly from official statistics, mainly due to a lack of knowledge regarding the specific shares of bio-based inputs in production.[2] In the recent past, the Joint Research Center (JRC) at the European Commission has attempted to remedy this situation by developing its own methodology. It is based on a combination of sectoral data from national evaluations and product-level assessments by industry experts of the fraction produced based on biological feedstocks. Thus, the share of bio-based production can be derived for those statistical sectors that are not fully attributable to the bioeconomy.[3] Although such a mixed approach does not offer the same degree of accuracy as the established national accounting standards, it represents a significant advance in comparison to estimates based purely on the official sector definitions.

Based on this methodology, the JRC publishes a regularly updated dataset on annual value added and employment in the EU bioeconomy and its subsectors.[4] Figure 2 depicts the evolution of value added (at factor costs and current prices) of the bioeconomy in the EU27 for the currently available time period (2008 to 2020). Accordingly, at the most recent data point of 2020, total annual value added generated by the bioeconomy amounted to EUR 664 billion. **Viewed in relation to a figure of EUR 2,601 billion for value added generated in primary and secondary sectors (sections A-E in the NACE classification),[5] the bioeconomy was responsible for a share of about 25 % of the income in the non-service part of the EU economy in 2020**. Estimated employment figures are similarly impressive. **For 2020, the estimated number of persons employed in the EU27 bioeconomy amounts to 17.2 million, which represented a share of 40 % in total non-service employment in the EU27**.[6] Across Member States, the overall relevance of the bioeconomy is subject to considerable variation, reflecting national differences in economic structure. The shares of the bioeconomy in total national value added in 2020 exhibit a range from 0.8 % (Luxembourg) to 10.5 % (Latvia) (see Figure A1 in the Appendix). In general, a clear west-east divide in the relative magnitude of the bioeconomy is observable. In large part, this is due to prevailing discrepancies in the role of agriculture as can be seen from the industrial part of production (share of bio-based manufacturing in total industrial value added). In this respect, a wide variation between countries is also evident, but one that is considerably less dependent on geography (see Figure A1).

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[2] Meyer, R. (2017). Bioeconomy strategies: Contexts, visions, guiding implementation principles and resulting debates. Sustainability, 9(6), 1031.

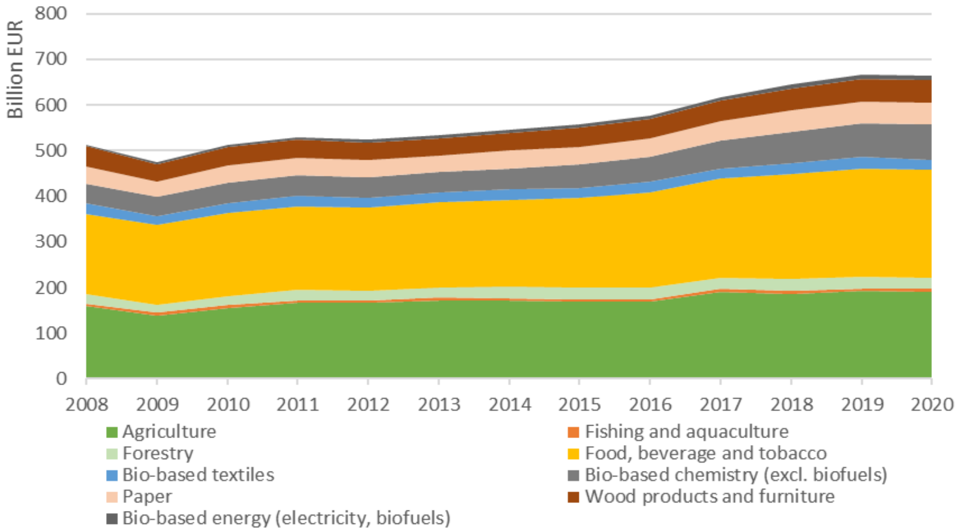
[3] Ronzon, T., Piotrowski, S., Tamosiunas, S., Dammer, L., Carus, M., & M'barek, R. (2020). Developments of economic growth and employment in bioeconomy sectors across the EU. Sustainability, 12(11), 4507.

[4] JRC (2024). Jobs and Wealth in the European Union Bioeconomy. Joint Research Centre – Knowledge Centre for Bioeconomy.

[5] Eurostat (2024a). Gross value added and income by A*10 industry breakdowns. Eurostat Database.

[6] Eurostat (2024b). Employment by A*10 industry breakdowns. Eurostat Database.

Figure 2: Value added of the EU27 Bioeconomy by sector



Source: JRC (2024); own illustration. Bio-based chemistry: Bio-based chemicals (excl. biofuels), pharmaceuticals, plastics and rubber.

Regarding sectoral composition, agriculture and the food industry do in EU-wide terms still account for the most significant parts of the bioeconomy value chains (see Figure 2). However, the steepest growth rates over the 2008-2019 period are observed for bio-based energy and bio-based chemistry, both in terms of value added (see Figure 2) and employment. While bio-based energy still constitutes in absolute terms only a very minor part of the bioeconomy, bio-based chemistry contributed about EUR 74 billion of value added in 2019 and EUR 79 billion in 2020. Hence, unlike other segments of the bioeconomy, bio-based chemistry did not experience a COVID-19-related contraction of value added in 2020, likely due to the increased demand for bio-based pharmaceuticals. They alone contributed EUR 65 billion of value added in 2020 but had in previous periods already represented by far the biggest subpart of bio-based chemistry. Moreover, bio-based chemistry has been characterized by particularly strong growth in labour productivity over recent years, but other segments of the bioeconomy also performed better than the EU economy in total (see Figure 3).

Not included in these official figures is the role of bioeconomy-related services. Ronzon et al. (2022) made an attempt to quantify the economic relevance of EU bioeconomy services by assigning bio-based shares to detailed NACE subsectors (4-digit level) in the service segment.[7] They distinguish four groups of bioeconomy services: services associated with tangible bio-based goods (e.g. trade, transport), natural environment related services (e.g. accommodation), knowledge-based services (e.g. research and education), support services (e.g. advertisement, public administration). They estimated an average annual value added for EU bioeconomy services over the period 2015-2017 of between EUR 589 billion and EUR 1,607 billion, varying with different assumptions on bio-based output shares. On average, trade and food services were identified as the most important subsegments of bioeconomy services.

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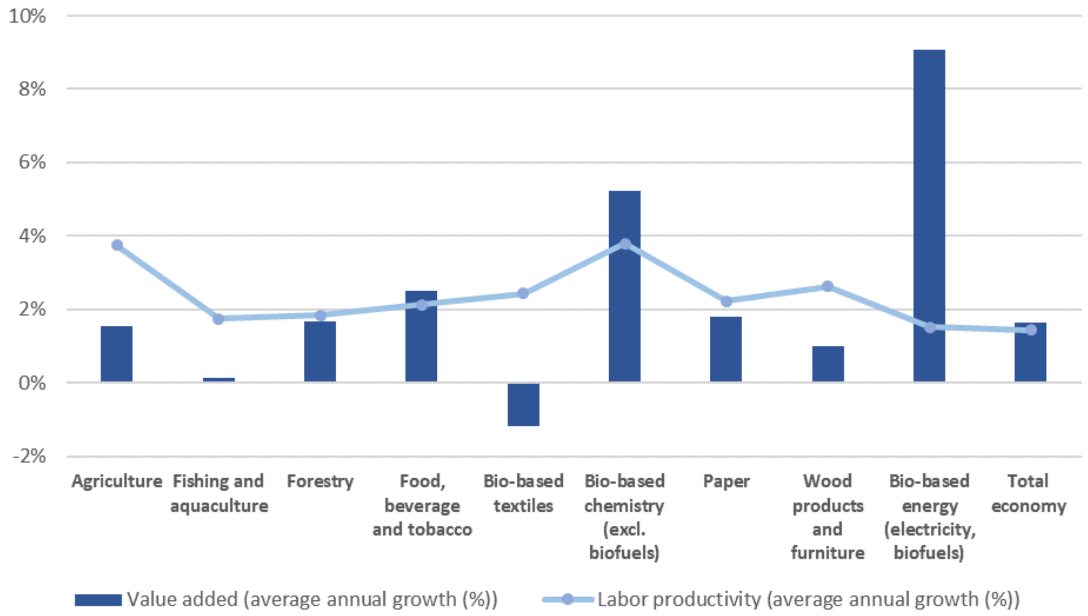
[7] Ronzon, T., Iost, S., & Philippidis, G. (2022). An output-based measurement of EU bioeconomy services: Marrying statistics with policy insight. Structural Change and Economic Dynamics, 60, 290-301.

Figure 3: Growth of value added and labour productivity in the EU27 bioeconomy 2008-2019



Source: JRC (2024); own calculations. Bio-based chemistry: Bio-based chemicals (excl. biofuels), pharmaceuticals, plastics and rubber.

The role of the EU bioeconomy as a cross-sectoral segment also indicates a strong and diverse interdependence with non-bio sectors of the EU economy. By means of an Input-Output-Analysis, Mainar et al. (2017) ascertained that input demand by the EU bioeconomy caused sizable multiplier effects.[8] They estimated that in 2010 for each EUR million spent on products of the bioeconomy EUR 0.57 million of value added were generated by bioeconomy value chains. About 60 % of this effect occurred outside biomass converting sectors, in particular in business services, trade and transportation. Particularly large positive repercussions emanated from the industrial part of the value chains. This further demonstrates the general economic significance of the bioeconomy beyond traditional food supply chains.

From a dynamic perspective, the bioeconomy can become a motor for societal innovation, with the potential to produce groundbreaking inventions of high cross-sector significance. The experience with vaccine innovation during the COVID-19 pandemics is a recent example of this. Back in 2009, in a Communication, the European Commission identified “industrial biotechnology” as one of five groups of strategically relevant Key Enabling Technologies (KET).[9] KETs are defined by the Commission based on a set of input- and output-related characteristics: high R&D intensity, strong need for skilled labour and capital, cross-cutting nature (touches various research disciplines) and role as enabler of further process, product and service innovation.[10] Based on this Communication, a High Level Group on Key Enabling Technologies was founded to provide recommendations on further technology development.

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[8] Mainar, A., Philippidis, G., & Sanjuán López, A. (2017). Analysis of structural patterns in highly disaggregated bioeconomy sectors by EU Member States using SAM/IO multipliers (No. JRC106676). Joint Research Centre (Seville site).

[9] European Commission (2009). Preparing for our future: Developing a common strategy for key enabling technologies in the EU. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2009) 512 final.

[10] European Commission (2012). A European strategy for key enabling technologies—A bridge to growth and jobs. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2012) 341 final.

In 2018, it redefined the set of KETs and spread bio-based technologies over two groups: life-science technologies (including neurotechnology, bioengineering, AI in biology, bioelectronics) and advanced materials (including biomaterials).[11] Moreover, as a result of an EU-led workshop among representatives from research and technology organizations, a proposal was made to define "biological transformation" as one of five new cross-cutting technology fields with particularly high potential, involving gene technology, neuro technologies, human-machine interaction and smart farming.[12] This highlights the strong interconnectedness between bio-based technologies and key research disciplines for the industrial transformation, in particular computer science and engineering. Further insights on biotech innovation patterns are provided in Section 3.

In addition to its relevance for long-term economic growth and innovation, the bioeconomy also has the potential to contribute to further strategic EU goals. Foremost, this concerns the goal of ensuring EU supply security in the field of basic resources. Not only is the domestic bioeconomy responsible for maintaining security of EU food supply. **It can also contribute to the goal of ending external dependence in the field of fossil resources, by replacing mineral oil and natural gas both in their roles as energy carriers (electricity generation from biomass, biofuels) and industrial feedstocks (biomass for basic chemicals and plastics)**. This is also acknowledged by the EU. For instance, the *RePowerEU* initiative, formulated as a response to supply threats caused by the Russian aggression against the Ukraine, includes concrete capacity targets for domestic biomethane as a versatile alternative to natural gas.[13]

Apart from security considerations, bio-based alternatives also represent in some respects a more environmentally friendly solution than fossil-based products. While the ecological performance of biofuels[14] and bio-based plastics[15] is subject to heated debate and requires thorough product-specific investigation, a more favourable Greenhouse Gas (GHG) balance is a typical result of life cycle comparisons with fossil-based variants.[16] CO_2 uptake during biomass cultivation offers the potential of a closed carbon cycle. Net GHG emissions are thus largely restricted to fossil energy use in production and transport. In combination with carbon capture processes, bio-based product chains even have the potential to become Negative Emission Technologies.[17]

Furthermore, the bioeconomy can contribute to another strategic goal formulated in recent years, the creation of a circular EU economy. First, by offering products which are biodegradable in a natural environment and/or compostable in industrial composting facilities, it adds variety to the range of available end-of-life treatment options. This is particularly useful for products where the costs of collection and recycling appear too high compared to the product value, e.g. for mulch films[18]. In these

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[11] TUM Global (2021). Key enabling technologies – key to enable Europe's future prosperity?. TUM Brussel Insights.

[12] Müller, J., & Potters, L. (2019). Future technology for prosperity: Horizon scanning by Europe's technology leaders. European Commission, Brussels.

[13] European Commission (2022a). REPowerEU: affordable, secure and sustainable energy for Europe. Communication COM(2022) 108 final.

[14] Elfasakhany, A. (2019). Biofuels in automobiles: advantages and disadvantages: a review. Current Alternative Energy, 3(1), 1-7.

[15] Ferreira-Filipe, D. A., Paço, A., Duarte, A. C., Rocha-Santos, T., & Patrício Silva, A. L. (2021). Are biobased plastics green alternatives? - a critical review. International Journal of Environmental Research and Public Health, 18(15), 7729.

[16] Yates, M. R., & Barlow, C. Y. (2013). Life cycle assessments of biodegradable, commercial biopolymers—A critical review. Resources, Conservation and Recycling, 78, 54-66.

[17] Wolf, A. (2024). Paving the way for a European carbon market. cepInput No.1/2024.

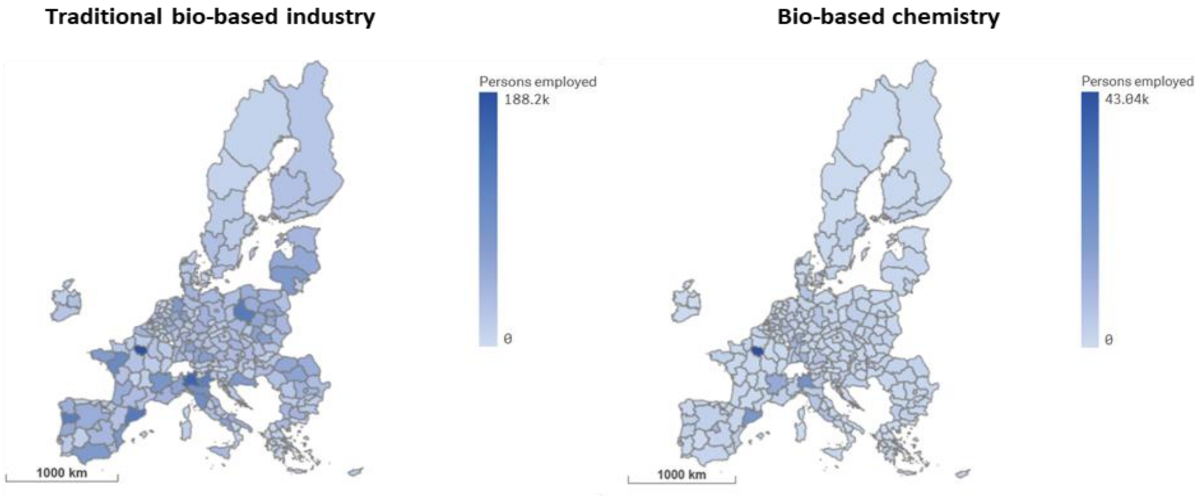
[18] Jandas, P. J., Mohanty, S., & Nayak, S. K. (2013). Sustainability, compostability, and specific microbial activity on agricultural mulch films prepared from poly (lactic acid). Industrial & Engineering Chemistry Research, 52(50), 17714-17724.

cases, natural degradation can help to avoid littering. Second, by utilizing innovative feedstock solutions like plant residuals, manure or food waste, the circularity of existing food supply chains can be directly increased and sustainability concerns regarding bio-based supply chains overcome (see Subsection 2.4). This helps to lower resource use in agriculture and its resulting environmental effects. In sum, **circularity is key for leveraging the strategic importance of the bioeconomy**. It strengthens the existing benefits of bio-based solutions by enhancing resource productivity, further improving the GHG balance and lowering the dependence on fossils.

2.3 Spatial clustering

While biomass production in the primary sector is closely linked to the regional distribution of arable land, facilities for the industrial processing of bio-resources show a more complex location pattern. Due to the nature of bio-based manufacturing as a cross-sectoral segment, it is difficult to statistically record the regional distribution of these economic activities. In 2023, the JRC published for the first time a pilot dataset with estimates of bioeconomy value added and employment at the level of EU NUTS-2 regions[19]. It is based on a combination of regional economic accounts and expert assessments of the share of bio-based production at sector level.[20] [21]Figure 4 shows information taken from the mapping tool on the distribution of employment in traditional bio-based industries and bio-based chemistry. Despite the distortive impact of size differences of NUTS-2 regions across Member States, a basic pattern emerges. Clear regional production centres can be identified in many Member States. This applies in particular to the non-traditional bio-based industries, i.e. bio-based chemistry in its widest sense. This pattern is consistent with the observation of agglomeration trends in other parts of the world, such as the extensive research on regional clustering in the US biotech industries.

Figure 4: Regional distribution (NUTS-2) of employment in bio-based manufacturing 2020



Traditional bio-based industry

Bio-based chemistry

Source: Lasarte López et al. (2023). Traditional bio-based industry: food, beverages and tobacco; bio-based textiles; wood products and furniture; paper. Bio-based chemistry: bio-based chemicals; bio-based pharmaceuticals; bio-based plastics and rubber.

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[19] Lasarte López, J. van Leeuwen, M., Rossi, C., Walter, M., González Hermoso, H. (2023). BioRegEU. Pilot dataset for Jobs and Value Added in the Bioeconomy of EU regions. European Commission, Joint Research Centre (JRC).

[20] Lasarte Lopez, J., Ronzon, T., van Leeuwen, M., Rossi Cervi, W., & M'Barek, R. (2022). Estimating employment and value added in the bioeconomy of EU regions (No. JRC128984). Joint Research Centre (JRC).

[21] According to personal communication with JRC, the dataset is still in a validation stage. It could therefore become subject to revisions in the future.

The economic literature on this topic discusses a variety of mutually overlapping causes. Basically, three typical explanations for agglomeration patterns can be distinguished. **The traditional Marshall-Arrow-Romer (MAR) externalities focus on industry-wide returns to scale as an explanation**.[22] By locating in the vicinity of other companies from the same industry, a company benefits from industry-wide economies of scale. These include the presence of a large number of suppliers of intermediate products and the availability of a local pool of adequately qualified workers. This reduces mismatching risks and transaction costs for the company. Another much-discussed advantage is the potential for local inter-firm knowledge spillovers via face-to-face communication, especially in the area of tacit, non-codifiable knowledge.[23] Recent research suggests that the basic advantages of face-to-face have survived in the digital era.[24] Taken together, these forms of externalities offer an explanation as to why knowledge-based and human capital-intensive industries such as biotech industries in particular are heavily concentrated in one region.

Jacobs' externalities offer another, complementary explanation for agglomeration.[25] **They are based on the effect of economy-wide returns to scope.** Accordingly, companies benefit from a diverse regional economic structure. It implies a greater variety of general inputs (professional services, infrastructure, institutions), easier access to technological solutions in other areas and a more stable demand base. Given the cross-cutting nature of biotechnologies and bio-based production, this is an impact channel of potentially high relevance. It is based on the notion of regions offering a diverse mix of institutions as an incubator.[26]

A third strand of the agglomeration literature, the New Economic Geography (NEG), does not refer to the role of spatially bounded externalities, but focuses on cost structures and market interactions as a reason for spatial concentration.[27] In this literature, agglomeration is not viewed purely from an industrial perspective, but as a process of joint clustering of producers and consumers/workers. One impact factor is the existence of high fixed costs in production. The associated (internal) returns to scale render locations near large sales markets attractive. The second impact factor is the existence of a preference for product variety ("love-of-variety") on the part of consumers/workers. A third factor is the role played by the cost of transportation. The basic models of the NEG show that a reduction in transport costs (e.g. as a result of technological progress) can initiate a process of extreme agglomeration, driven by the mutual reinforcement of scale economies and love-of-variety.[28] This type of explanation also seems particularly applicable to the capital-intensive and knowledge-intensive parts of bio-based production where fixed costs for equipment and research and development (R&D) are high and, at the same time, downstream processing is characterized by a high degree of complexity/diversity of input needs.

Overall, all current theories offer good explanations for the emergence and stability of spatial clusters of bio-based industries. However, they do not explain where exactly in space such clusters

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[22] Henderson, V. (1997). Externalities and industrial development. Journal of urban economics, 42(3), 449-470.

[23] Van der Panne, G. (2004). Agglomeration externalities: Marshall versus Jacobs. Journal of evolutionary economics, 14, 593-604.

[24] Atkin, D., Chen, M. K., & Popov, A. (2022). The returns to face-to-face interactions: Knowledge spillovers in Silicon Valley (No. w30147). National Bureau of Economic Research.

[25] See Henderson (1997).

[26] Neffke, F., Henning, M., Boschma, R., Lundquist, K. J., & Olander, L. O. (2011). The dynamics of agglomeration externalities along the life cycle of industries. Regional studies, 45(1), 49-65.

[27] Krugman, P. (1998). What's new about the new economic geography?. Oxford review of economic policy, 14(2), 7-17.

[28] Krugman, P. (1991). Increasing returns and economic geography. Journal of Political Economy, 99, 483-99.

emerge and which impulses are needed to change existing agglomeration structures. There is extensive empirical literature on this topic, which focuses on the situation of the US biotech industry.

One area of the literature examines the role of individual regional anchor players who provide an initial impetus for the development of clustering structures. These can be well-established anchor firms that use a new technology for the first time on an industrial scale. They generate (spatially bounded) knowledge externalities and strengthen regional business formation through spin-off firms founded by employees. At the same time, they ensure the local presence of a pool of specialized input suppliers. As a result, a cluster develops around their specialized expertise.[29] Such a firm-driven regional path dependence stresses the fact that agglomeration economies are not only driven by overall industry size, but also by the distribution of individual firm sizes.

Another anchor examined is the regional presence of so-called star scientists. These are scientists who are in the exclusive possession of breakthrough knowledge (which can partly be non-codifiable) and are linked to strong personal networks both within and beyond academia.[30] They can trigger successful regional business formation for the commercial exploitation of their own knowledge. Their reputation is advantageous when seeking access to capital and skilled workers. They can also improve the performance of incumbent regional biotech firms. Zucker et al. (2002) show that research cooperation (measured in research articles) between company scientists and external star scientists leads to a significant increase in the number and citation rate of company patents. Physical proximity facilitates the establishment of such research contacts.[31]

The role of local human capital in general beyond individual star scientists is also the subject of intense debate. It has several functions. Firstly, it serves as a source for filling high-skilled positions in local research, manufacturing and industry-related business services.[32] In the knowledge-intensive biotech segment, the qualification level of the local labour pool naturally plays a particularly important role. Secondly, it represents a source of future regional start-ups when it comes to the commercialization of innovations generated by the local activities of research institutions. Empirical research points to the particular importance of region-based academic entrepreneurs for regional start-up dynamics.[33]

Another strand of the literature focuses on access to financial capital as a location factor. Its relevance is particularly emphasized for young biotech companies as, typically, large sums of money have to be spent on R&D for many years before upscaling allows them to generate profits.[34] It is initially difficult to assess whether products will actually succeed on the market. Success rates tend to be low. **Investments in biotech start-ups are therefore high-risk and require profound knowledge of technologies and industry structure on the part of external investors, who need to be specialized**

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[29] Feldman, M. (2003). The locational dynamics of the US biotech industry: knowledge externalities and the anchor hypothesis. Industry and innovation, 10(3), 311-329.

[30] Zucker, L. G., & Darby, M. R. (1996). Star scientists and institutional transformation: Patterns of invention and innovation in the formation of the biotechnology industry. Proceedings of the National Academy of Sciences, 93(23), 12709-12716.

[31] Zucker, L. G., Darby, M. R., & Armstrong, J. S. (2002). Commercializing knowledge: University science, knowledge capture, and firm performance in biotechnology. Management science, 48(1), 138-153.

[32] Fritsch, M. (2005). Do regional systems of innovation matter. The New Economy in Transatlantic Perspective-Spaces of Innovation, Abingdon: Routledge, 187-203.

[33] Kolympiris, C., Kalaitzandonakes, N., & Miller, D. (2015). Location choice of academic entrepreneurs: Evidence from the US biotechnology industry. Journal of Business Venturing, 30(2), 227-254.

[34] Lerner, J. (2000). The government as venture capitalist: the long-run impact of the SBIR program. The Journal of Private Equity, 55-78.

venture capital companies. These facts underline the beneficial role of local knowledge dissemination networks between founders, venture capitalists and established producers. Through regional spillovers of tacit industry knowledge, potential investors can better assess the chances of success. This increases their overall willingness to invest. Founders can benefit from local investors not only through the capital they provide, but also by tapping into their personal contacts (e.g. investment banks and potential customers) and their local industry knowledge.[35] This means that access to venture capital also has a spatial dimension that favours geographical proximity. Indeed, empirical research comes to the conclusion that growth in the number of employees and the sales of start-ups is greater when they are located near venture capital companies.[36] Local venture capital funding focuses much more strongly on early-stage companies than does transregional funding.[37]

The role of public infrastructure as a location factor is also an object of research. **In addition to the general importance of cross-industry basic infrastructure (transport and communication networks, access to energy and amenities), the importance of public knowledge infrastructure is particularly high for the biotech segment.** Local universities and public research institutes specialized in biotech not only provide a significant share of the pool of potential high-skilled workers for the industry, but also contribute directly to the entrepreneurial dynamism of the region through academic spin-offs, e.g. for the exploitation of university patents. University spin-offs were crucial to the birth and early development of the US biotech industry.[38] Such firms are often founded in close proximity to the academic institution which engendered them, also in order to maintain the informal flow of knowledge. Research-focused universities are of particular significance.[39]

Finally, the importance of social institutions as intangible regional location factors must not be overlooked. First, this concerns the area of public administration, e.g. the level of local taxes and levies, the amount of rigor in the application of environmental protection regulations and the duration of permit processes. Research shows that, in addition to the quality of industry regulation, the stability of regulation also has a positive value in itself.[40] The establishment of clear and reliable rules offers planning security for long-term investments as well as policy guidance for future technological development. Second, it concerns the existence of (formal and informal) private networks for knowledge exchange. They create trust through stable personal relationships and thus provide the basis for continuous mutual knowledge exchange as a motor for regional innovation capacity (see above).[41] Moreover, leisure-related networks increase the quality of life of employees and thus contribute to the attractiveness of local employers.

In summary, **the emergence of biotech clusters presents itself as an interplay of positive feedback effects, in which the persistent generation of new scientific knowledge and its capitalization through risk-friendly entrepreneurship and external venture capital are the central driving forces**. Figure 5 attempts to summarize the major interconnections uncovered by the literature. In theory, the policy

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[35] Powell, W. W., Koput, K. W., Bowie, J. I., & Smith-Doerr, L. (2002). The spatial clustering of science and capital: Accounting for biotech firm-venture capital relationships. Regional Studies, 36(3), 291-305.

[36] See Lerner (2000).

[37] See Powell et al. (2002).

[38] Prevezer, M. (1997). The dynamics of industrial clustering in biotechnology. Small business economics, 9, 255-271.

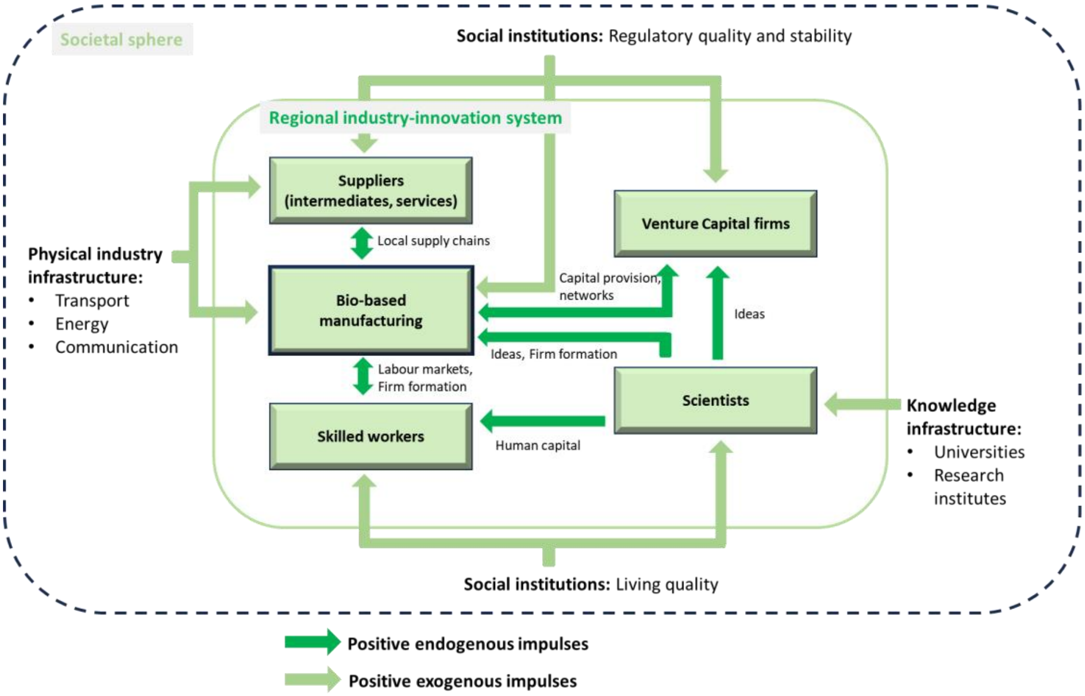
[39] Owen-Smith, J., & Powell, W. W. (2004). Knowledge networks as channels and conduits: The effects of spillovers in the Boston biotechnology community. Organization science, 15(1), 5-21.

[40] Sable, M. S. (2007). An analysis of the role of government in the locational decisions of Cambridge biotechnology firms (Doctoral dissertation, Massachusetts Institute of Technology).

[41] Kim, M. K., Harris, T. R., & Vusovic, S. (2009). Efficiency Analysis of the US Biotechnology Industry: Clustering Enhances Productivity. AgBioForum, 12(3&4), 422-436.

recipes for building a vital regional bioeconomy are thus simple: local policy-makers should provide a science-focused high-tech infrastructure and minimize administrative investment barriers. In practice, however, the path-dependency of development renders successful implementation difficult. To build new clusters (or to overcome the growth limits of existing ones), both financial capital and embodied knowledge (scientists, supervisors, managers) bound up in established structures elsewhere must be inclined to relocate. This difficulty is aggravated by mutual forces of attraction: a strong impulse is needed to detach individual elements from a functioning cluster network. Such an impulse requires policy-making to focus clearly on eliminating the existing obstacles to development.

Figure 5: Interplay of agglomeration forces in biotech industries



Source: own illustration

2.4 Barriers to growth

The variety of complex process steps involved in extracting and processing a biological feedstock makes business models highly vulnerable to external factors. This concerns at least four intertwined dimensions: the economic, the environmental, the social and the technological. In this respect, four main growth barriers common to many current supply chains can be identified.

1. Lack of venture capital culture

High technological complexity and demand uncertainty give rise to the emergence of a "valley of death" in the application of biotech innovations, in particular for the stage between proof-of-principle and industrial upscaling.[42] **Access to private venture capital is a crucial driving force for successful commercialization, as highlighted by the literature on spatial agglomeration** (see Subsection 2.3). Instead of growing slowly and painfully based on own resources, a firm can speed up its growth stage by receiving leverage from experienced investors, which in addition often provide valuable industry

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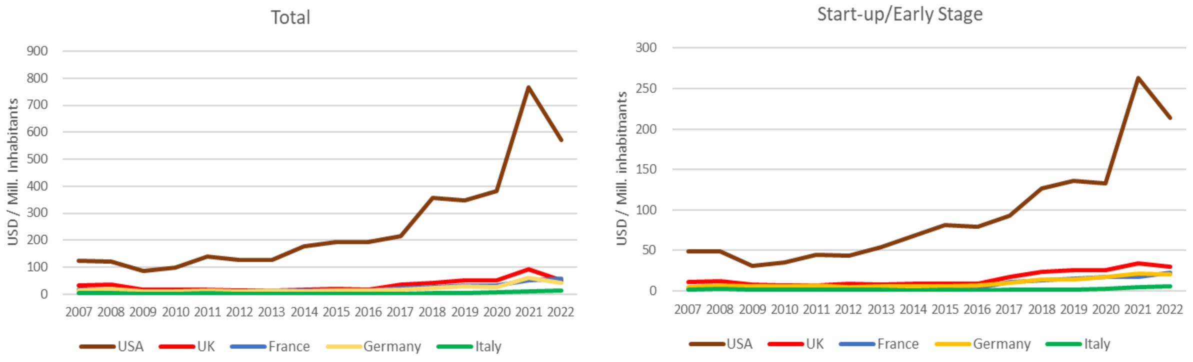
[42] Kampers, L. F., Asin-Garcia, E., Schaap, P. J., Wagemakers, A., & Dos Santos, V. A. M. (2021). From innovation to application: bridging the valley of death in industrial biotechnology. Trends in Biotechnology, 39(12), 1240-1242.

knowledge and contacts. This key role played by venture capitalists as a growth driver of innovative industries is severely underutilized in Europe. For example, the number of venture capital (VC) deals struck in Germany and France over the period 2019-2021 in the biotech field was far below the figures reported for the US.[43] While in the segment of industrial biomaterials only three VC deals were reported for Germany and five for France, 68 were reported for the USA. In the segment of pharmaceuticals, these fundamental discrepancies are of similar magnitude. In terms of investment amounts, the gap is even wider. Despite its high relevance for the EU Green Deal, for example, only EUR 29 million in venture capital was invested in the biomaterials segment in 2019-2021, compared with EUR 99 million in France and EUR 1.56 billion in the United States.[44] This is not a peculiarity of biotech investments. OECD figures on economy-wide VC investments[45] indicate that it is a sign of a general discrepancy in venture capital culture between the two sides of the Atlantic (see Figure 6). Over the last fifteen years, annual per capita VC investment in the US continuously reached a completely different order of magnitude than that of the major European economies, and the gap has widened in recent years as regards both total investments and VC specifically for the start-up stage.

Figure 6: Country comparison of annual VC investments per million inhabitants



Source: OECD (2024); World Bank (2024), own calculations.

2. Skilled labour shortage

The high level of knowledge intensity and short innovation cycles in the biotech sector also imply a high demand for highly-skilled workers with distinct expertise in various natural sciences as well as in engineering. This segment is therefore particularly affected by the tougher competition for workers trained in the Science, Technology, Engineering and Maths (STEM) field. **In its annual analysis of labour supply and demand in different occupations, the European Labor Authority (ELA) has diagnosed a dominance of STEM-related classifications within the group of occupations with widespread shortages**.[46] For instance, 15 EU Member States identified applications programmer and software developer as occupations where there are shortages. In the case of software developers, seven Member States even reported a severe shortage. In particular, segments of the bioeconomy that require highly specialized skills, such as genetic medicine[47], are exposed to a high risk of skill mismatch, causing significant planning uncertainties and a need to invest heavily and continuously in active

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[43] KfW Research (2022). Venture Capital: Marktchancen in Zukunftstechnologien. Nr. 392/2022.

[44] See KfW Research (2022).

[45] OECD (2024a). Enterprise statistics - Venture capital investments. OECD.STAT. Organization for Economic Co-operation and Development, Paris.

[46] ELA (2022). EURES Report on labour shortages and surpluses 2022. European Labour Authority.

[47] Chakraverty, A. (2021). Skilled Labor Shortages Impact Cell And Gene Therapy Manufacturing. Labiotech.

recruitment. General demographic change, which affects the Member States to varying degrees, threatens to exacerbate the shortage of talented young scientists for industrial research, and thus also the inflow of fresh ideas to European bio-based industries, in the long term. At the same time, Europe faces strong competition in the global recruitment of specialized professionals and must compete above all with the high level of financial attractiveness of the US biotech industry.

3. Heterogeneity of product properties

Bio-based industry products are highly specific in their technical properties, not only across but also within the segments of the bioeconomy. Foremost, this applies to chemical products like biofuels and bio-based plastics. This heterogeneity affects key usage properties. In the case of bio-based plastics, for instance, it includes factors such as material strength, durability and temperature sensitivity, partly influenced by the use of certain additives. While technical variety is a benefit making bio-based products suitable for a wide range of applications, it imposes high information requirements on the user side. The heterogeneity also stretches to environmental impacts. For instance, the available options for end-of-life treatment differ considerably between specific bio-based plastic materials. This starts with the fact that not all bio-based plastics are biodegradable. Those that are differ substantially in the time horizon and environmental requirements of a natural degradation process.[48] Biodegradability, in turn, does not ensure the compostability of products in an industrial composting facility. The ability to recover bioplastic waste through mechanical or chemical recycling is also highly material-specific and sometimes requires specific process routes separate from conventional plastics. **In sum, this creates considerable uncertainty about the actual sustainability of bio-based solutions from a life cycle perspective**. Surveys show that this uncertainty can contribute to reservations on the part of consumers with respect to bio-based products.[49] In turn, significant resources are required for information campaigns and labelling.

4. Ecological boundaries

In addition to the food industry, an integral part of the remaining bioeconomy rests on the use of cultivated plants as biological feedstocks. While current total land use for feedstock plants is not a cause for concern, it still sets long-term limits on the spread of bio-based solutions. The various types of pollutant and nutrient emissions occurring in farming (e.g. through the use of synthetic fertilizers and land machines) burden local ecosystems and endanger biodiversity by contributing to e.g. soil acidification and eutrophication. As a consequence, food-plant based products like current commercial bioplastics typically exhibit a mixed performance in Environmental Life Cycle Assessments (ELCA). They clearly perform better than their fossil-based counterparts in GHG emissions and fossil resource use, but worse in some local environmental damage categories. Moreover, negative environmental effects from land preparation can also arise in cases where no direct land conversion was necessary. The trade-off with food production implies that the cultivation of plants for use as industrial feedstock may lead to deforestation in other areas in order to provide alternative acreage for food generation. Identifying the environmental consequences of this indirect land use change is the subject of intense

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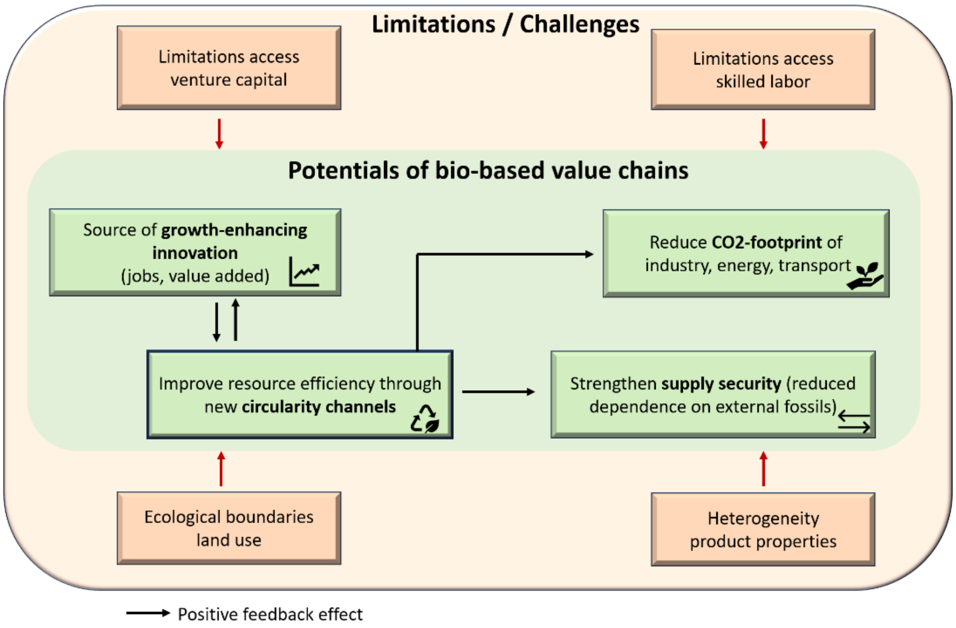
[48] Folino, A., Pangallo, D., & Calabrò, P. S. (2023). Assessing bioplastics biodegradability by standard and research methods: current trends and open issues. Journal of Environmental Chemical Engineering, 109424.

[49] Fletcher, C. A. (2022). Is the consumer experience creating barriers for the effective uptake and disposal of bioplastics?. Clean Technologies and Recycling, 2(4), 308-320.

methodological debate in the ELCA literature.[50] A general recommendation is that while being difficult to measure, estimates of these effects should not be swept under the carpet in a consistent ELCA. **Against this background, a medium-term switch to second-generation (e.g. corn stover, sugarcane bagasse) and third-generation (e.g. food waste, microalgae) feedstocks will be inevitable for overcoming resource-related growth barriers**. These are based on residuals, waste or non-agricultural organisms and thus do not compete with food production. In turn, ELCAs tend to diagnose significantly smaller ecological side effects at the stage of feedstock extraction.[51] However, while a wide range of such solutions have been developed and tested, commercial upscaling as a prerequisite for cost reductions is still sparse. As a consequence, high input needs in industrial processing tend to limit price competitiveness and worsen the environmental performance of innovative feedstock solutions.[52]

Figure 7: Overview on potentials and challenges of bio-based value chains



Source: own illustration.

3 Innovation dynamics in the bioeconomy

3.1 Classes of biotechnologies

A widely consulted definition by the OECD describes biotechnology as "the application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services."[53] This definition is deliberately kept very broad. It comprises not only all technologies related to the physical use of biomass but also those used for its analysis (e.g. construction of gene sequences in bioinformatics). In addition to

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[50] Brandão, M., Heijungs, R., & Cowie, A. R. (2022). On quantifying sources of uncertainty in the carbon footprint of biofuels: crop/feedstock, LCA modelling approach, land-use change, and GHG metrics. Biofuel Research Journal, 9(2), 1608-1616.

[51] Wellenreuther, C., Wolf, A. (2020). Innovative feedstocks in biodegradable bio-based plastics: a literature review. HWWI Research Paper 194.

[52] Wellenreuther, C., Wolf, A., & Zander, N. (2022). Cost competitiveness of sustainable bioplastic feedstocks–A Monte Carlo analysis for polylactic acid. Cleaner Engineering and Technology, 6, 100411.

[53] OECD (2013). Biotechnology. In: OECD Factbook 2013: Economic, Environmental and Social Statistics. Organization for Economic Co-operation and Development, Paris.

cutting-edge laboratory technologies at cellular or molecular level, all traditional bio-based production technologies are covered. Based on this definition, the use of biotechnologies by mankind can be traced at least as far back as the emergence of agriculture in the Neolithic Revolution. According to a common view, the origin of the wave of modern commercial molecular biotechnologies dates back to the 1970s, when a series of patents on techniques for moving genes between organisms was filed in the US.[54] A ruling by the US Supreme Court in 1980, which declared genetically modified microorganisms to be patentable, then provided the impetus for a wave of patenting activities in the field of microbiology.[55]

To bring clarity to the discussion about the variety of biotech solutions, it has become common practice to differentiate technology classes according to colour. There is no generally accepted colour code, but certain meanings have become established for individual colours. Table 1 shows the frequently used classification by Kafarski (2012).[56] Three classes are at the centre of attention: green, red and white biotechnologies. Green biotechnologies are associated with the greatest political and legal controversy, especially in connection with the genetic modification of food crops. Red biotechnologies have gained significant attention in recent years, especially in the context of the massive surge in the development of messenger RNA (mRNA) vaccines at the beginning of the COVID-19 pandemic. White biotechnologies have already been under development for several decades. Their specific potential lies in the possibility of replacing fossil resources as industrial feedstocks. Yellow biotechnologies can be regarded as a traditional branch of biotechnologies. However, they also involve leading-edge techniques, e.g. the use of functional microorganisms for improving food quality or the establishment of innovative bioconversion systems for the recycling of food waste. In addition, the golden and violet biotechnologies have established important cross-sectoral segments that offer essential services for all other areas of biotechnologies, and bridge the gap to disciplines like computer science, law and the social sciences. **A common feature of all these biotechnology classes is their strong dependence on basic research and the dynamics of fundamental breakthrough discoveries**.[57]

Table 1: Colour classes of biotechnologies

Colour	Class description	Examples
Green	Applications in agriculture	Plant cell cultivation, Molecular plant engineering
Red	Applications in pharmaceuticals	Vaccines, Hormone therapy
White	Applications in (non-food) manufacturing	Bio-based polymers, Biofuels
Yellow	Applications in the food industry	Brewing, Food waste recycling
Blue	Applications in fisheries and aquafarming	Genetic modification of fish, Use of microalgae
Brown	Applications in management of deserts	Cultivation of desert crops, Water management
Gold	Processing of biological data	Software solutions, Lab practices
Violet	Discussion of law and ethical issues	Biotech philosophy, Specialized legal services

Source: Kafarski (2012); own representation.

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[54] See Feldman (2003).

[55] US Supreme Court (1980). Diamond v. Chakrabarty, 447 U.S. 303 (1980). No. 79-136. United States Supreme Court.

[56] Kafarski, P. (2012). Rainbow code of biotechnology. Chemik 66(8): 811-816.

[57] NAS (2020). Safeguarding the Bioeconomy. National Academies of Sciences, Engineering, and Medicine. National Academies Press.

3.2 Activities in global comparison

Any attempt to compare innovation success is confronted with immediate measurement difficulties. This is partly due to the ambiguity of the term “innovation”. In the general sense of the word, innovation can refer to a new idea, its concretization in the form of a design or product or the process of developing new ideas, designs or products. In the economic context, innovation is usually understood as the market launch of new products or processes that differ from existing ones in relevant characteristics. It is therefore based on prior research and development. Overall, innovation is therefore best described as a multi-stage process of cumulative discovery: researchers discover new mechanisms through basic research, which are taken up by product development, tested, piloted and finally commercialized on markets. Innovation success thus depends on a whole range of players with interests that are not always homogeneous. Technology Readiness Levels (TRLs) are a common way of characterizing the stages of innovation processes. The official TRL scale was developed by NASA and adopted by the EU for the Horizon 2020 framework program. It consists of nine levels - from concept development to commercial readiness.[58]

From an economic point of view, it makes sense to start measuring innovation at the point where the prospect of commercialization of inventions becomes evident through the registration of property rights. Patent data is often therefore the basis for output-based innovation indicators. Their limitations are well known.[59] They do not provide information about the actual subsequent market success of patented inventions and their general societal impact. They are also not a perfect measure of innovation at the development stage, as many types of inventions are not patentable for technical or legal reasons. In the field of biotechnology, the EU ban on patenting particular plants and animal varieties is worth mentioning.[60] Nevertheless, the main advantages include the high degree of international harmonization and the high level of technological detail in patent statistics. The International Patent Classification (IPC) system enables an extremely fine-grained subdivision according to fields of technology.[61] A delimitation of biotechnologies based on patents is therefore much more accurate than on the basis of production statistics (see Subsection 2.2). In addition, information on innovation networks via cross-referencing (citations) and supra-regional cooperation between institutions and inventors is available.

For the international comparison of innovation activities in the field of biotechnology, we use data from PATSTAT, the worldwide patent statistical database of the European Patent Office (EPO).[62] It is one of the world's most comprehensive patent databases and a popular choice for innovation analyses. For the definition of biotechnologies, we apply the OECD's list of biotechnology IPC classes according to the 2016 update.[63] For all of the classes contained in this list, data on all registered patents over the period 2000 to 2022 was retrieved via search queries in PATSTAT. The data collected for each patent includes affiliation to the specific technology class, patent family and number of citations by other patent documents. The dataset generated contains a total of 282,817 observations. In the next step,

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[58] NASA (2024). Technology Readiness Levels. The National Aeronautics and Space Administration.

[59] Wydra, S. (2020). Measuring innovation in the bioeconomy–Conceptual discussion and empirical experiences. Technology in Society, 61, 101242.

[60] European Union (1998). Directive 98/44/EC of the European Parliament and of the Council of 6 July 1998 on the legal protection of biotechnological inventions.

[61] WIPO (2024): International Patent Classification (IPC). World Intellectual Property Organization.

[62] EPO (2024). PATSTAT – Backbone dataset for statistical analysis. European Patent Office.

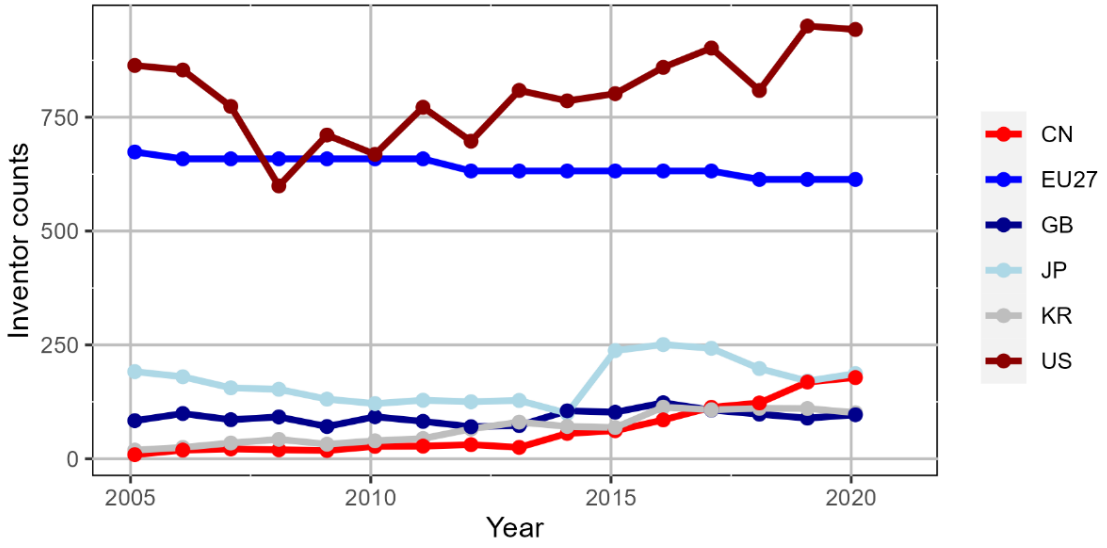
[63] Friedrichs, S., van Beuzekom, B. (2018). Revised proposal for the revision of the statistical definitions of biotechnology and nanotechnology. OECD Science, Technology and Industry Working Papers, 2018/01, OECD Publishing, Paris.

it is merged with data from the OECD REGPAT database.[64] This contains additional information on the names and residential addresses of the inventors registered in the patents, thus enabling a detailed spatial allocation. Compared to using the addresses of the applicants, which in the case of multinational enterprises can be a parent company or an affiliate located far away from R&D activities, this results in a more precise spatial picture of innovation.

The number of patent applications is a common indicator for quantifying patent activity. However, there are signs of structural breaks for biotech patents over time. A phase of strong global patent activity in the early 2000s ended in 2005 with a significant drop and many years of stagnation. For the period after 2020, the current version of REGPAT also shows signs of gaps in coverage. For the following analyses, we therefore limit our attention to the period 2005 to 2020. For a country comparison, we must consider that often several people are registered as the inventors of a patent, who may be located in different countries. As is common in the literature, we account for this by applying an equal share for each inventor which serves as a weight. For instance, in the case of a patent with eight registered inventors, each inventor is assigned a share of 0.125. Then, we calculate the total biotech innovation activity of a country as the sum of the shares of inventors residing in the respective country ("inventor counts").

Figure 8 first shows the development of these inventor counts for the EU27 as a whole in comparison to the most active third countries. It reflects the dominant role of the USA as a driver of innovation whose lead over the EU has widened in recent years. **While the figures for US-based inventors indicated activity growth over several years in the decade up to 2020, the figures for the EU stagnated**. Moreover, in per capita terms, EU patenting activity was consistently lower than e.g. figures for South Korea (KR). The EU also lost ground to China (CN) in the same period. In absolute terms, the People's Republic is still a long way from reaching the patent figures of Europe and the USA but showed strong growth from 2014 and was already able to catch up with Japan (JP) and South Korea.

Figure 8: Evolution of biotech patenting activities in major inventor countries worldwide



Sources: EPO (2024); OECD (2024b); own calculations.

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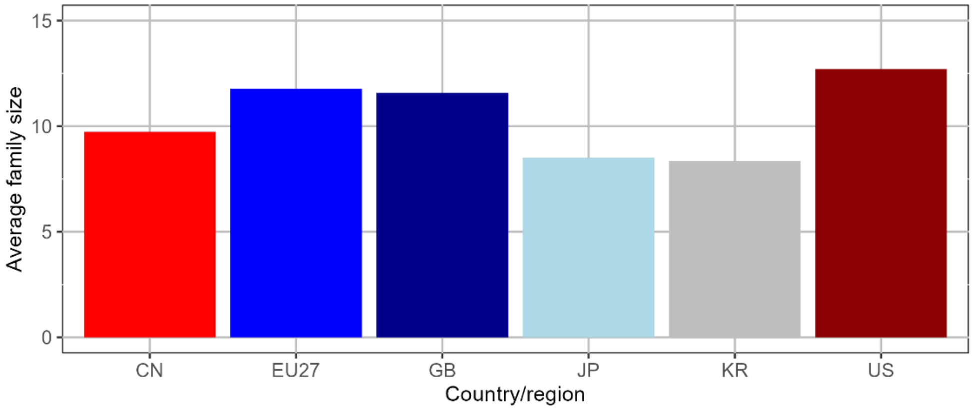
[64] OECD (2024b). Intellectual property (IP) statistics and analysis. Organization for Economic Co-operation and Development, Paris.

A look at the quality of patent applications offers an important complementary perspective. A variety of measures for recording patent quality are discussed in the literature. The patent family size indicator contained in PATSTAT makes it possible to measure quality on the basis of the degree of dissemination. All patent applications that have the same or very similar technical content are grouped together to form a patent family. Such a family can arise, for example, when an original application is extended to additional countries (and patent offices). The family size thus indicates the expected global market potential of innovations. Below, we use the average family size of all biotech patents involving domestic investors as an indicator for national patent quality. Figure 9 shows the average family sizes over the period 2005 to 2020. In this respect, the performance of EU27 patents was significantly above the values for the East Asian comparison countries. **This suggests a high average global dissemination of EU biotech inventions. Again, however, the performance did not quite reach the level of the US.**

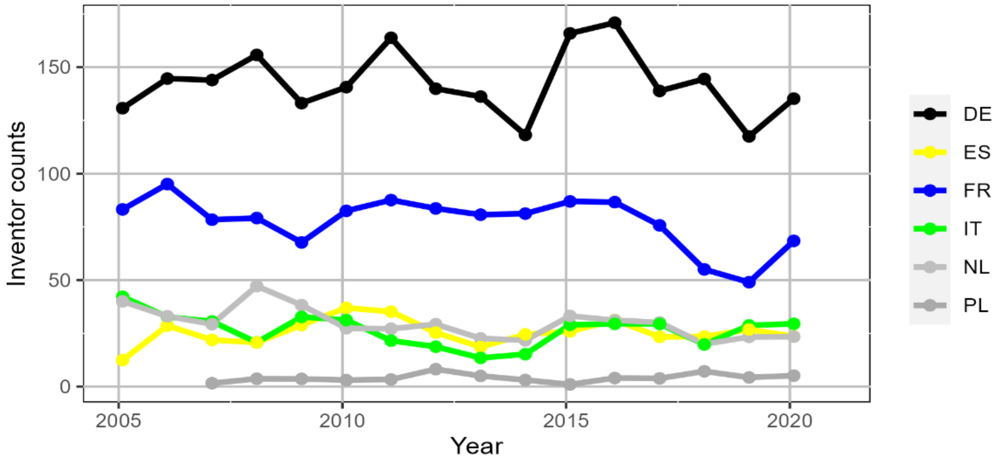
Figure 9: Average biotech patent family sizes by country 2005-2020



Sources: EPO (2024); OECD (2024b); own calculations.

In a comparison of the largest EU economies, Germany exhibited the highest level of patent activity in every year, in absolute terms (see Figure 10). However, the annual fluctuations were particularly pronounced. In per capita terms, France's innovation activity was higher in some years. In per capita terms, Italy, Spain and Poland exhibited comparatively low inventor counts.

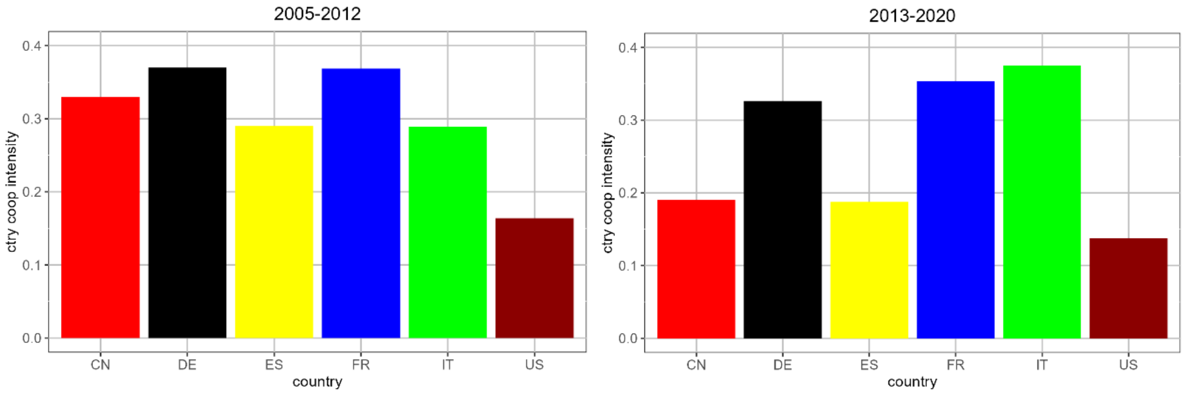
Figure 10: Evolution of biotech patenting activities in selected EU Member States



Sources: EPO (2024); OECD (2024b); own calculations.

In addition, our data set also allows us to make country comparisons on the extent of international cooperation in innovation activities by comparing the addresses of the inventors registered in the patent applications. Figure 11 shows the intensity of cross-country cooperation in biotech patents for a selection of countries. The intensity of cooperation is measured as the proportion of biotech patents with inventors from the respective country in which inventors from other countries were involved. There are clear differences among the EU countries as well as in comparison to China and the USA. In the period 2005-12, the intensity of cooperation was particularly high among German and French inventors. In the subsequent period 2013-2020, the cooperation intensity of Germany lowered a little. The consistently higher international cooperation intensity of the depicted EU Member States compared to the US is striking. In parts, this reflects the high domestic innovation potential of the US. **Moreover, when comparing the two periods, the significant decline in China's international cooperation intensity is striking.** This may to some extent be the outcome of a policy-induced cutting of research ties, but it could also illustrate a reduced need for external knowledge inflow.

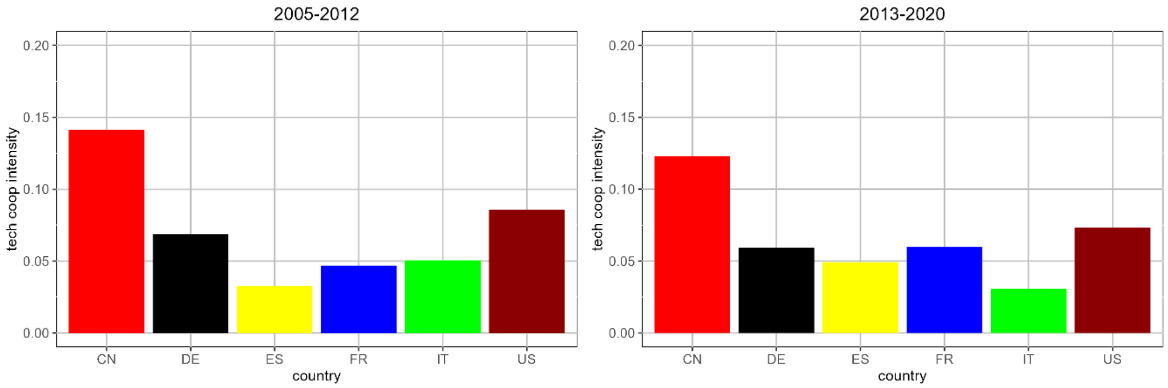
Figure 11: Intensity of cross-country cooperation in biotech patents by country



Sources: EPO (2024); OECD (2024b); own calculations.

Finally, we can also illustrate cooperation in technological terms. Some patent applications are assigned to several technology fields within the IPC system. Figure 12 shows the intensity of cross-field cooperation, based on a delineation of IPC codes at the 4-digit level. In both periods, the EU members exhibited lower values for this indicator than China and the USA. China in particular stands out with a high cross-field intensity. To a certain extent, these differences are likely to be an expression of different national specialization strategies within the broad area of biotechnologies. **Nevertheless, the bottom line is that China's biotech innovations showed a comparatively strong outreach to various technology fields.** In principle, this promises additional potential for utilizing generated knowledge for future follow-up research.

Figure 12: Intensity of cross-field cooperation in biotech patents by country

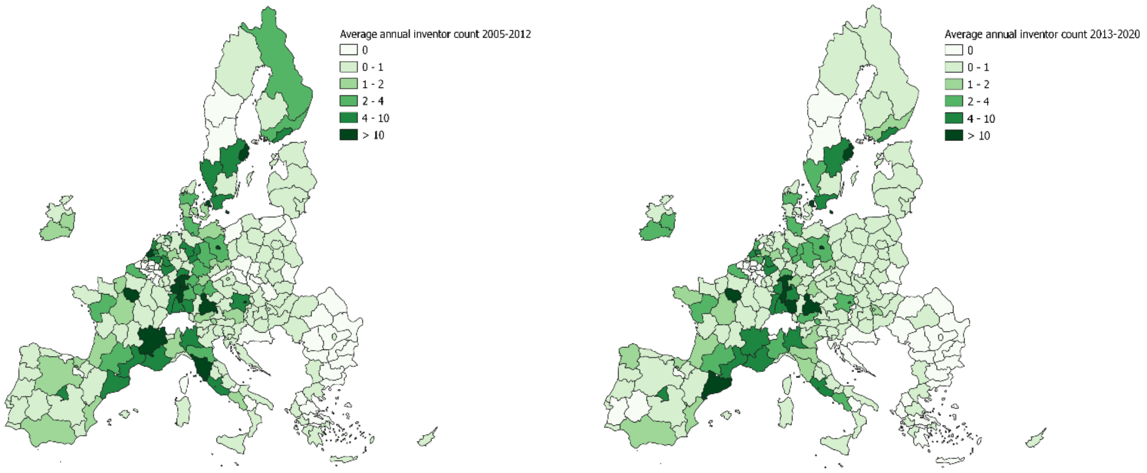


Sources: EPO (2024); OECD (2024b); own calculations.

3.3 Innovation hotspots in the EU

Our database enables an even stronger spatial breakdown of patent activity in the field of biotechnologies within the EU. REGPAT also contains indicators for the allocation of inventors' addresses of residence to NUTS regions. In the following, we choose the NUTS-2 level for the spatial comparison. Figure 13 shows the average annual level of our *inventor count* measure, broken down by the periods 2005-12 and 2013-20. In general, a clear east-west divide is evident. Within the western Member States, clear spatial centres of innovation activity can be identified. This is in line with the natural agglomeration tendency (see Subsection 2.3) of the industry. The NUTS 2 regions with the strongest research activity in both periods were *Île-de-France* (FR10), followed by *Upper Bavaria* (DE21) and *Hovedstaden* (DK01). All three regions are characterized by a generally high degree of industrial agglomeration, which points to the importance of cross-industrial external scale economies. Macro-regional clusters of great importance in both periods were the south of France (plus Catalonia) and the south/south-west of Germany. In addition to this continuity, a comparison of the two periods also shows signs of a gradual shift in innovation activity. For example, some regions within the Eastern European Member States were able to gain ground in the more recent period.

Figure 13: Distribution of biotech patent applications by NUTS-2 region (inventor count measure)



Sources: EPO (2024); OECD (2024b); own calculations.

The discovery of the underlying causes of these differences in regional innovation activity has been the subject of extensive research literature in recent years. Fornahl et al. (2011) showed that the patent intensity of biotech companies in Germany depends positively on research cooperation with other companies and on being located in a cluster.[65] Graf & Broekel (2020) document a positive influence of project-specific R&D subsidies on the development of regional R&D networks in biotech clusters.[66] Engel et al. (2013) show the importance of competition-oriented research funding for persistent regional research cooperation.[67] In general, the role of research collaboration in various dimensions (between regions, sectors, institutions) has been a frequent object of interest in innovation economics. The results indicate that cooperation has a potentially high significance for the generation of knowledge spillovers. Its effects on innovation activity, however, strongly depend on the forms of cooperation and local conditions. For example, Kekezi et al. (2022) ascertain that the influence of interregional research cooperation on future knowledge creation is highly dependent on the sector of the cooperating companies.[68] Roesler & Broekel (2017) document the fact that universities with a strong research base acting as regional gatekeepers have a major influence on the formation of knowledge networks in German biotech research.[69] Balland & Boschma (2021) show that a high technological complementarity of partner regions strengthens the positive effect of interregional research cooperation on future patent activities.[70] Caragliu & Nijkamp (2012) shed light on the key role of regional cognitive capital for exploiting new knowledge obtained e.g. through interregional knowledge spillovers.[71]

We will now examine the factors behind the pattern of biotech innovations in the EU NUTS-2 regions. The patent information taken from PATSTAT enables us to distinguish between a quantitative and a qualitative dimension. We measure the quantitative annual level of biotech innovation in a region by the number of different patent families for which inventors from the region have filed patent applications (*fam_count*). Multiple applications within the same patent family are thus only counted once. This aims to ensure that we only count technically different inventions (see previous subsection). The quality of patents is much more difficult to assess, as no direct conclusions can be drawn about the future market value of an invention from the patent data itself. In the following, we reflect the quality dimension using two different measurements that are inherent to the patent system. The first measurement is the average size of the patent families for which inventors from the respective region have filed applications (*fam_avg*). It is intended to reflect the international scope of regional patents in the global patent system. The second measurement is the average rate of forward citations of biotech patents from regional inventors (*cite_count*). This indicates the embeddedness in global cross-referencing networks. To account for the fact that younger patents tend to have fewer forward

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[65] Fornahl, D., Broekel, T., & Boschma, R. (2011). What drives patent performance of German biotech firms? The impact of R&D subsidies, knowledge networks and their location. Papers in regional science, 90(2), 395-418.

[66] Graf, H., & Broekel, T. (2020). A shot in the dark? Policy influence on cluster networks. Research Policy, 49(3), 103920.

[67] Engel, D., Mitze, T., Patuelli, R., & Reinkowski, J. (2013). Does cluster policy trigger R&D activity? Evidence from German biotech contests. European Planning Studies, 21(11), 1735-1759.

[68] Kekezi, O., Dall'erba, S., & Kang, D. (2022). The role of interregional and inter-sectoral knowledge spillovers on regional knowledge creation across US metropolitan counties. Spatial Economic Analysis, 17(3), 291-310.

[69] Roesler, C., & Broekel, T. (2017). The role of universities in a network of subsidized R&D collaboration: The case of the biotechnology-industry in Germany. Review of Regional Research, 37, 135-160.

[70] Balland, P. A., & Boschma, R. (2021). Complementary interregional linkages and Smart Specialization: An empirical study on European regions. Regional Studies, 55(6), 1059-1070.

[71] Caragliu, A., & Nijkamp, P. (2012). The impact of regional absorptive capacity on spatial knowledge spillovers: the Cohen and Levinthal model revisited. Applied Economics, 44(11), 1363-1374.

citations, we divide the number of average citations per region by the global average values for biotech patents from the respective year.

Our particular focus is on the impact of cross-regional and interdisciplinary research cooperation. The promotion of strong supra-regional innovation networks has always been an objective of EU R&D support, both in general and specifically for focal areas such as biotechnologies. Interdisciplinarity is also recognized as a key to solving complex real-world problems, as is evident in the mission-oriented approach of the current Horizon Europe research framework program.[72] So far, however, there is still a lack of evidence for the actual significance of this maxim for research success in the biotech sector, especially with regard to the quality of the resulting patents. We first approach these relationships by illustrating the bilateral correlation patterns. Figure A2 in the Appendix shows scatter plots with regional average values for the period 2013-2020. Our three innovation measurements are each compared with the interregional cooperation intensity (*reg_coopins*). Like the international cooperation intensity from the previous subsection, it measures the proportion of patent applications by regional inventors in which inventors from other NUTS-2 regions were involved. The plots indicate a clear positive correlation between the cooperation figures for all three patent measurements. Above all, almost all regions with far below-average cooperation intensity exhibited weak patenting activities in terms of both quantity and quality.

In order to arrive at testable relationships, influences on innovation activities that are related to time and place should be considered. Our regional patent dataset, which is extensive in terms of both time and space, provides an ideal basis for this. In the following, we use it for our own econometric analysis. Following a procedure commonly referred to in the literature, we merge the patent dataset with a set of EU regional indicators from Eurostat.[73] One limitation in choosing regional control variables is that no sector-specific regional characteristics are available, as bio-based production is inherently cross-sectoral (see Subsection 2.2). Due to the generally weaker resolution of economic accounting measures, such as value added at the regional level, these cannot be constructed from existing data for NUTS-2 regions. However, we can draw on indicators for high-tech manufacturing and research sectors, which are generally collected on a regular basis. Another limitation is the need for a sufficiently long time series for a dynamic analysis. Some interesting regional indicators (e.g. from the EU Regional Competitiveness Index) that have only been collected very recently cannot therefore be incorporated.

Our strategy is to estimate separate regression models for each of the three previously derived innovation measurements. In order to highlight any differences in the correlations, we use the same set of explanatory variables in each case. These must be of potential general relevance as inputs. We approximate the extent of direct regional R&D input using Eurostat data on human resources in sciences and technology, specifically the number of scientists and engineers working in the region (*HRST*). Potential effects of the general level of regional economic agglomeration on research success (e.g. through industry-external economies of scale, see Subsection 2.3) are considered by using regional GDP per capita as a control variable (*GDP_pc*). We approximate the general level of local cognitive capital (a possible influencing factor on the adoption of created knowledge and its implementation in future innovation)[74] based on the share of 25–64-year-olds with tertiary education (*tert_ed*).

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[72] European Commission (2021). Horizon Europe – The EU Research and innovation program 2021-2027. Presentation.

[73] Eurostat (2024c). Regional statistics by NUTS classification. Eurostat Database.

[74] See Caragliu & Nijkamp (2010).

In addition to the intensity of supra-regional cooperation, we also use the intensity of interdisciplinary cooperation, taken from the patent statistics, as a measure of cooperation (*tech_coopins*). However, we can only measure the latter very indirectly, as we do not have any information on the scientific background of the individual inventors. We identify cooperation on the output side via the potentially multiple IPC codes that are assigned to an invention. Specifically, we infer the existence of cooperation if codes from at least two different IPC categories are assigned to an invention, with categories being limited to the 4-digit level. One hypothesis is that multi-categorical patents create particular potential for follow-up innovations, as the knowledge generated is relevant to more than one field of technology. Moreover, we use the lag in the inventor counts indicator as a further explanatory factor from the patent statistics *(inv_count*). It measures the potential importance of past regional engagement in patent activities for the quantity and quality of future innovations. It thus reflects the dynamic moment in the innovation process, the utilization of acquired knowledge for subsequent innovations. In order to reduce endogeneity problems and account for the time lag in the occurrence of innovation successes, all the other explanatory factors mentioned above are included in the model in lagged form, following a recommendation in the literature.[75] Finally, in order to check for the influence of time-dependent effects and persistent country-specific factors (national incentives, institutional setting), we include country and year dummies in the model.

When selecting the estimation method, the significant number of zero values for the dependent variables in the initial dataset must be handled with care. Not all NUTS-2 regions possessed R&D capacities in the biotech segment. Some regions did not generate any biotech patents over the entire period of the sample. These were omitted from the estimation, as it is unlikely that any serious efforts were made to conduct commercial biotech research. Another group of regions did generate biotech patents within the sample period, but not in every year. Since we cannot assume that these patterns are random, we should not simply eliminate these zero values. Instead, we draw on the classic approach of a censored regression model based on James Tobin,[76] the so-called Tobit-I model. The mechanism underlying the observations is split into two processes. A process that determines the existence of positive values (i.e. the existence of patent activity) and a process that determines the level of positive values (i.e. the extent of patent activity). Following a standard procedure, we apply the same set of explanatory factors to both processes.

The pooled Tobit model with time and country fixed effects is estimated for each of the three dependent variables on the basis of a total of 2,212 observations. For the practical estimation, we use the statistical package *crch* implemented in the software *R*. It performs a maximum likelihood estimation while controlling for conditional heteroscedasticity of the error terms.[77] Table A1 in the Appendix shows the coefficient estimates for the base models (coefficients of time and country dummies are not shown for reasons of space).[78]

Despite clear discrepancies, some qualitative characteristics can be observed equally for all three dependent variables. In addition to the expected positive and significant influence of the HRST variable, this applies to the consistently significant positive effect of regional cooperation intensity.

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[75] See Kekezi et al. (2022).

[76] Tobin, J. (1958). Estimation of relationships for limited dependent variables. Econometrica: journal of the Econometric Society, 24-36.

[77] Messner, J. W., Mayr, G. J., & Zeileis, A. (2016). Heteroscedastic Censored and Truncated Regression with crch. R J., 8(1), 173.

[78] Please note that due to the censoring constraint, the coefficients do not equal the marginal effects.

Since we check for GDP per capita and past regional inventor activity, this is not simply an expression of a stronger spatial outreach of research-focused agglomeration regions. For a given level of absolute inventor activity, a higher proportion of cross-regional cooperation in patenting is associated with more research success in the future, both in terms of the quantitative (larger number of different patent families) and qualitative (larger size of patent families, more forward citations) dimensions of biotech innovation. The second cooperation variable, the measure of cross-field cooperation, is consistently insignificant. In view of the measurement difficulties, however, this does not necessarily indicate a lack of importance of interdisciplinarity for future biotech innovation. Moreover, an unobserved form of value added could consist of increased patenting activities in technology groups outside our delineation of biotechnologies. This suggests the inclusion of additional data sources (e.g. at company level) to reflect the institutional background of the registered inventors.

The measured effect of the human capital variable is also highly significant. Given the simultaneous consideration of scientific human resources, this is not simply an expression of the size of the local pool of researchers. **Rather, it points to the important role of general cognitive resources for the translation of research findings into new patentable knowledge**. Such an effect is not necessarily isolated. In fact, a positive interaction with the amount of research knowledge gained in the past would be conceivable. One hypothesis is that the positive effect of gained knowledge on future innovation is greater in regions with strong cognitive capital. We test this hypothesis using a second model variant in which interaction terms between human capital and inventor count (*tert_ed X inv_count*) as well as between human capital and the cross-regional cooperation intensity (*tert_ed X reg_coopins*) are included as additional variables. The estimation results are shown in Table A2 in the Appendix. First of all, it is evident that the base term of *reg_coopins* remains consistently positive and highly significant in this model variant. The same applies to both interaction terms. **Accordingly, a higher regional level of human capital not only strengthens the positive association between past regional patent activity and the quantity and quality of current innovation. It also strengthens the role of cross-regional cooperation.** This suggests that cognitive capital is also important for the process of utilizing knowledge inflows for the creation of new patentable knowledge.

Of course, given the lack of measures to check for differences in regional infrastructure, great caution must be exercised in inferring on causality. Nevertheless, the estimates as a whole highlight two important facts. First, more intense cross-regional collaboration in biotech research is often associated with wider future dissemination of the knowledge created by regional inventors in the global patent system. Second, a high level of education in the local population is a supportive factor for this association. This also holds when comparing EU regions with similar past levels of innovation success, i.e. it is not simply a reflection of regional differences in overall biotech research competence.

4 Development strategies at EU level

4.1 The evolution of EU bioeconomy policies

The field of biotechnologies and bio-based manufacturing has long been a subject of the European Commission's strategic considerations. This started with the implementation of the EU Framework program in Biotechnology and Life Sciences back in 1982, setting the stage for continuous EU funding activities in the field of biotechnology research.[79] In 2002, the Commission presented its first *Life Sciences and Biotechnology Strategy*.[80] Its motivation was the quantum leap in the technological readiness of areas such as genetic engineering and the economic and ethical questions that arose from this. Europe was faced with a growing global dominance of US companies in this segment, expressed in significantly higher turnover and employment as well as a much broader product range of the US bioeconomy. With its strategy, the Commission aimed to strengthen the global competitiveness of European companies, while at the same time addressing ethical concerns in a way that guaranteed societal support for the technologies concerned. In a mid-term review of the strategy published in 2007, the Commission framed the innovation goals by putting them in a broader economic context, promoting the concept of a *Knowledge Based Bio-Economy* (KBBE).[81] It stressed the fact that the development and application of biotechnologies had stretched far beyond exclusive biotech companies and diffused into a wide range of traditional industrial sectors. In light of increasing environmental concerns related to fossil resource usage, biotechnologies were seen as a key factor for sustainable growth of the European economy.

This new positioning set the stage for the **first EU Bioeconomy Strategy** published in 2012.[82] It covered the whole spectrum of bioresource use in the economy, including food supply chains. With this holistic approach, the Commission went beyond existing concepts of bio-based manufacturing, e.g. postulated by the OECD.[83] It was not only supposed to enhance European competitiveness, but also to provide assistance for coping with a range of global societal challenges, including climate change, food security and sustainable resource management. The ambition for the EU was to take a leading role in a future transition towards a global bioeconomy. Past initiatives were to be extended to broaden their industrial scale, putting special emphasis on the implementation and scaling of new bio-based value chains.[84] To achieve this, a streamlining of bioeconomy-related policies conducted at the various administrative levels was considered essential, especially with respect to the goal of fostering innovation in priority areas.

The strategy involved an action plan consisting of three pillars. The first pillar covered measures to stimulate investment in knowledge, innovation and skills. This primarily involved R&D support through Horizon 2020, the EU's research and innovation funding program from 2014-2020, where technology solutions relating to bioresources addressed several of the specific objectives defined for the priority area “societal challenges” (total budget: EUR 29.6 billion).[85] The second pillar involved measures to strengthen policy dialogue and policy monitoring systems. European Innovation Partnerships (EIPs) were assigned a key role to achieve alignment on bioeconomy-related policies in the EU, leading to the

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[79] Aguilar, A., Magnien, E., & Thomas, D. (2013). Thirty years of European biotechnology programmes: from biomolecular engineering to the bioeconomy. New biotechnology, 30(5), 410-425.

[80] European Commission (2002). Life sciences and biotechnology – a strategy for Europe. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions COM(2002) 27.

[81] European Commission (2007). Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions on the mid-term review of the Strategy on Life Sciences and Biotechnology. COM(2007) 175 final.

[82] European Commission (2012). Innovating for Sustainable Growth: A Bioeconomy for Europe. Communication from the Commission to the European Parliament, the Council, the Eco-nomic and Social Committee and the Committee of the Regions. COM(2012) 60 final.

[83] Bell, J., Paula, L., Dodd, T., Németh, S., Nanou, C., Mega, V., & Campos, P. (2018). EU ambition to build the world’s leading bioeconomy - Uncertain times demand innovative and sustainable solutions. New biotechnology, 40, 25-30.

[84] Patermann, C., & Aguilar, A. (2018). The origins of the bioeconomy in the European Union. New biotechnology, 40, 20-24.

[85] European Commission (2014). Horizon 2020 – Priority area ‘societal challenges’.

launch of an EIP for Agricultural productivity and Sustainability (EIP-AGRI).[86] The third pillar covered measures to enhance domestic competitiveness. Establishing integrated and diversified biorefineries, which made efficient use of the available bioresources, was considered the key to both competitive and sustainable supply chains.

In sum, the first bioeconomy strategy was an expression of a more holistic understanding of the growth conditions for the European bioeconomy. Access to local resources and diffusion of knowledge were now identified as central prerequisites not only for innovation activities, but also for building and maintaining manufacturing capacities in Europe. Interregional and interinstitutional cooperation and a supply chain perspective on competitiveness were recognized as key to identifying and meeting these needs. The new institutions created on the basis of the strategy subsequently gave rise to a wealth of new cooperation activities. In 2014, the *Bio-based Industries Joint Undertaking* (BBI JU), a PPP between the European Commission and the Bio-based Industries Consortium, was established.[87] Its central purpose was to foster radical innovation, starting from basic research through to demonstration and then to commercialization. Through public funding guarantees, it was designed to provide a stable long-term framework for the industry, allowing for a strategic programming of R&D activities.[88] In 2021, it was replaced by the Circular Bio-based Europe Joint Undertaking established under the umbrella of Horizon Europe, which continues the activities with a specific focus on the EU sustainability objectives.[89] Since 2014, the Joint Undertaking has according to its own information invested about EUR 904 million from EU sources in projects. This involves a range of flagship projects spread across Europe, which operate innovative pilot production plants mostly based on the use of second and third-generation feedstocks (by-products, waste streams).[90]

The Commission's review of the bioeconomy strategy in 2017 saw early signs of success. It highlighted the increase in dedicated EU research funding for the bioeconomy, reaching a level of EUR 4.52 billion under Horizon2020, a more than doubling of the previous framework program. It also pointed at the widespread adoption of dedicated bioeconomy strategies at the national level in the EU, and the increasingly important role of the bioeconomy in regional innovation strategies. At the same time, it diagnosed a lack of detailed monitoring capabilities, both related to economic success and the sustainability impacts.[91] As an immediate response, the Bioeconomy Knowledge Centre was established as a dedicated information source within the organizational structure of the Joint Research Centre.[92] Moreover, while maintaining the strategy's goals, the Commission saw the need to adapt the action plan to align its measures to changing EU policy priorities. This concerned the increased dominance of the concept of circularity, as expressed by the EU's first Circular Economy Action Plan.[93]

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[86] European Commission (2023a). Research and innovation – European Innovation Partnerships (EIPs).

[87] European Council (2014). Council regulation (EU) No 560/2014 of 6 May 2014 establishing the Bio-based Industries Joint Undertaking.

[88] See Mengal et al. (2018).

[89] European Council (2021). Council regulation (EU) 2021/2085 of 19 November 2021 establishing the Joint Undertakings under Horizon Europe and repealing Regulations (EC) No 219/2007, (EU) No 557/2014, (EU) No 558/2014, (EU) No 559/2014, (EU) No 560/2014, (EU) No 561/2014 and (EU) No 642/2014.

[90] Circular Bio-based Joint Undertaking (2023). A competitive bioeconomy for a sustainable future.

[91] European Commission (2017). Review of the 2012 European Bioeconomy Strategy. Staff Working Document.

[92] European Commission (2023b). Knowledge Centre for Bioeconomy.

[93] European Commission (2015). Closing the loop - An EU action plan for the Circular Economy. Communication from the Commission to the European Parliament, the Council, the Eco-nomic and Social Committee and the Committee of the Regions. COM(2015) 614 final.

The 2018 update of the bioeconomy strategy accounted for these considerations by redefining the pillars of the action plan.[94] **The first pillar consisted of measures to "strengthen and scale-up the bio-based sectors, unlock investments and markets"**. Thus, it was intended to combine the first and third pillar of the original strategy (see above). As a financial support instrument, besides ongoing R&D support through the EU's 2021-2027 research program Horizon Europe, the Commission proposed for the first time an EU fund exclusively dedicated to financing investments in the circular bioeconomy. This impetus subsequently contributed to the launch of the Circular Bioeconomy Fund in 2020, a public-private venture capital fund specializing in growth-stage companies in the EU.[95] It is endowed with a contribution of EUR 100 million from the European Investment Bank. The originally planned total endowment of EUR 250 million has by now grown to EUR 300 million thanks to additional private investors.[96]

The second pillar outlined measures to "deploy local bioeconomies rapidly across Europe". This signalled a new perspective: it highlighted the potential of the bioeconomy to become a tool for regional economic development and restructuring. In particular, the promotion of more efficient and sustainable generation of biomass in farming and forestry was considered key for unlocking the growth potential of rural areas. To this end, the Commission announced a Strategic Development Agenda (not yet implemented) and proposed several pilot actions specifically designed to foster the development of a bioeconomy in rural, coastal and urban areas. This included both stakeholder engagement (formation of committees and meeting formats) and targeted financial support to projects through the Horizon program and the European Maritime and Fisheries Fund (EMFAF).

Finally, the third pillar of the action plan is entitled "Understand the ecological boundaries of the bioeconomy". With this, the Commission was aiming to improve overall knowledge about the sustainability impact of the bioeconomy, in particular the natural limits to biomass supply and its ecological side effects. The knowledge acquired was supposed to improve the monitoring of the entire strategy. Thus, its objective resembles the second pillar of the original strategy, but with an even stronger focus on environmental monitoring. The task of collecting the relevant data was assigned to the Knowledge Center for Bioeconomy. Besides establishing a monitoring system, the pillar involved the announcement of funding for research projects aiming to improve biodiversity in land and marine ecosystems at the microbial level. This is seen as a promising way to eliminate potential trade-offs between sustainability and productivity in biomass generation.[97]

Thus, the 2018 update by and large continued the path of the original strategy but departed from it by setting a stronger focus on ecological side effects and the interplay with regional economic development. In other words, the spatial and social dimensions of the bioeconomy significantly gained in importance. Figure 14 summarizes the gradual extension of the EU policy approach over time.

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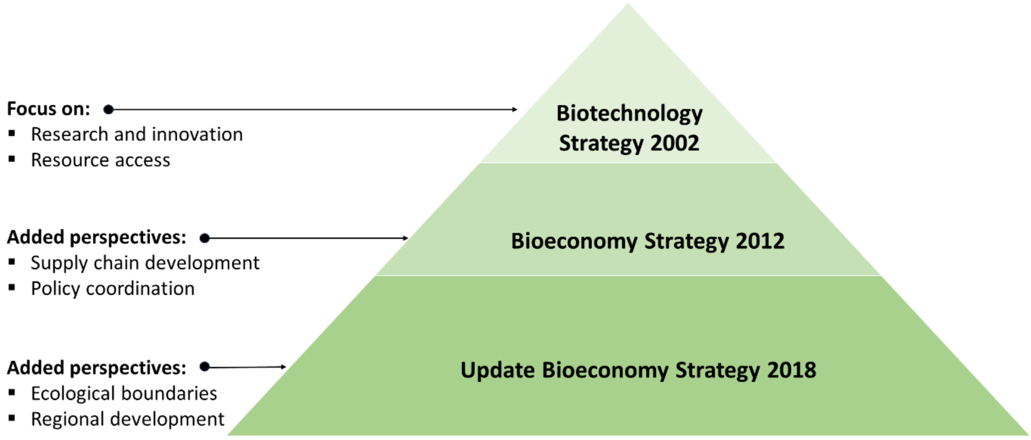
[94] European Commission (2018). A sustainable Bioeconomy for Europe: Strengthening the connection between economy, society and the environment. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2018) 673 final.

[95] ECBF (2023). Venture capital for transformation. European Circular Bioeconomy Fund.

[96] ECBF (2021). Growth capital for sustainable transformation to a bio-based circular economy: EU-initiated impact fund oversubscribed with € 300 million. European Circular Bioeconomy Fund. Press release, February 23 2021.

[97] Gupta, A., Singh, U. B., Sahu, P. K., Paul, S., Kumar, A., Malviya, D., ... & Saxena, A. K. (2022). Linking soil microbial diversity to modern agriculture practices: A review. International Journal of Environmental Research and Public Health, 19(5), 3141.

Figure 14: Evolution of scope in EU Bioeconomy strategies



Source: own illustration.

4.2 The bioeconomy in the EU Green Deal framework

The presentation of the European Green Deal by Commission President von der Leyen on 11 December 2019 marked the beginning of a new era in EU climate policy.[98] The ambitious goal of a climate-neutral EU economy by 2050 was combined with an economic policy agenda focused on green growth, including just transition mechanisms for EU regions threatened by structural change. One core element of the implementation was the European Green Deal Investment Plan, which included new EU financing instruments for the green transformation (InvestEU, Just Transition Mechanism). A total of 1 trillion euros in sustainable investments are to be mobilized in the period 2021-2030, financed from private and public sources.[99] The second core element was a large number of new regulatory initiatives to accelerate the reduction of emissions and other societal goals (circularity, pollution, biodiversity), spreading across all sectors of the EU economy.

The future production and utilization of biomass in the EU plays an important role for the sustainability goals of the Green Deal. Accordingly, there are numerous overlaps between the objectives of the Bioeconomy Strategy 2018 and the target categories of the Green Deal (see Figure 15). On the one hand, this is directly evident in the Farm-to-Fork Strategy relating to food supply chains published on 20 May 2020.[100] Its goal of ensuring the provision of fair, healthy and environmentally friendly food is congruent with the goals of food security and sustainable resource management contained in the bioeconomy strategy. A series of measures was announced aimed at promoting the reduction of potentially environmentally harmful substances in agriculture (pesticides, fertilizers), introducing uniform labelling of sustainable food, halving per capita food waste and promoting research and innovation in the field of food production. However, recent political communications have given rise to speculation that the Commission may cease to pursue important parts of the initiative, such as the

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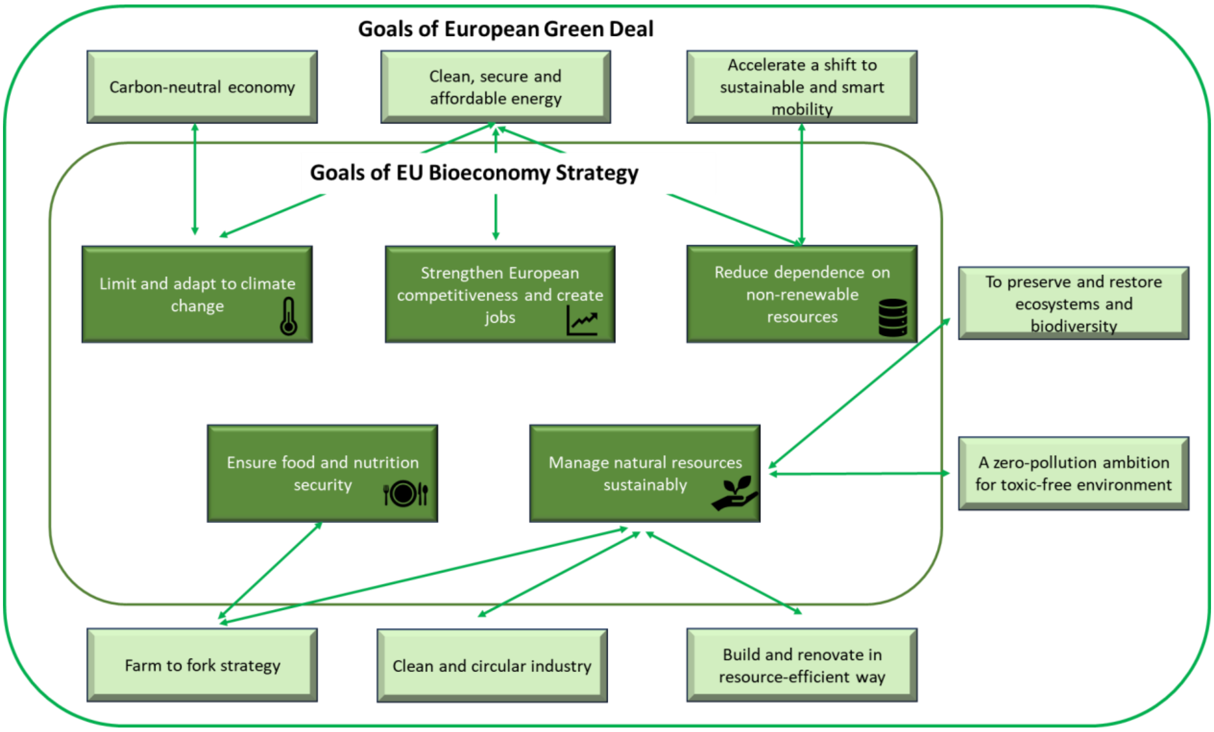
[98] European Commission (2019). The European Green Deal. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2019) 640 final.

[99] European Commission (2020a). Sustainable Europe Investment Plan – European Green Deal Investment Plan. Communication from the Commission to the European Parliament, the Council, the Eco-nomic and Social Committee and the Committee of the Regions. COM(2020) 21 final.

[100] European Commission (2020b). A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2020) 381 final.

planned framework for a sustainable food system.[101] Moreover, the Green Deal objective for the conservation and restoration of ecosystems and biodiversity makes full reference to the bioeconomy. The direct link to the Bioeconomy Strategy 2018 is its goal of a sustainable management of biomass. It provided the impulse for an EU biodiversity strategy for 2030, published on 20 May 2020[102], setting the stage for the proposal for a Regulation on nature restoration released on 22 June 2022.[103] It foresees legally binding minimum targets for the share of areas in the EU to be restored, as well as the obligation for Member States to design binding national restoration plans with concrete subgoals and measures. After heated debates, a provisional agreement was reached in November 2023, defining a target to restore at least 20 % of the EU's land and sea areas by 2030.[104]

Figure 15: Links between the goals of the European Green Deal and the EU Bioeconomy Strategy



Source: own illustration.

Other Green Deal goals and initiatives do not exclusively target the bioeconomy but are nevertheless highly relevant for bio-based supply chains. This is true of the goal for a clean and circular industry. As explained in Subsection 2.2, the use of biogenic resources as industrial raw materials in the production of basic chemicals, plastics etc. not only has the potential to lower or avoid net emissions of harmful substances but, in the case of some products, also offers additional end-of-life options to boost circularity principles in supply chains. First, a major initiative relating to circularity was provided by the

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[101] EURACTIV (2023). Agrifood Brief: Farm to Fork is dead, long live the strategic dialogue! 15 September 2023.

[102] European Commission (2020c). EU Biodiversity Strategy for 2030 - Bringing nature back into our lives. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2020) 380 final.

[103] European Commission (2022b). Proposal for a Regulation of the European Parliament and of the Council on nature restoration. COM(2022) 304 final.

[104] European Council (2023). Nature restoration: Council and Parliament reach agreement on new rules to restore and preserve degraded habitats in the EU. Press release, 9 November 2023.

update of the Circular Economy Action Plan published on 11 March 2020.[105] It announced numerous product- and sector-specific legislative proposals to strengthen circular supply chains, including areas relevant to the bioeconomy such as food production, packaging, plastics and textiles. This led, among other things, to a proposal for a revision of the Packaging and Packaging Waste Regulation,[106] which raises ambitions on recycling targets and requires very lightweight plastic carrier bags to be compostable, and contains a proposal for the revision of the Waste Framework Directive, which sets additional targets for waste reduction in the food and textiles sectors[107]. Second, the EU Strategy for Plastics in the Circular Economy published on 16 January 2018 aimed specifically to curb plastic waste and improve the profitability of plastic recycling in the EU.[108] It has so far given rise to a Directive banning the use of certain types of single-use plastics,[109] rules restricting the use of microplastics in production[110] and a Communication clarifying conditions for the appropriate use of the terms “biobased, “biodegradable” and “compostable” in the context of plastics.[111]

The Green Deal objective of establishing a carbon-neutral economy also interacts in various ways with the bioeconomy. Besides reducing net greenhouse gas emissions through its use as a feedstock and heat source in industry, sustainably generated biomass can also contribute to improving the GHG balance of the energy (biomass in electricity production), building (biogenic insulation material) and transport sector (biofuels). The legislative focus so far has been the “Fit-for-55” package, a comprehensive set of laws governed by the EU mid-term goal of reaching a 55 % reduction in greenhouse gas emissions by 2030 compared to 1990. Among the several proposals included, particular attention has been given to biomass by the Regulation on land use, land-use change and forestry (LULUCF) adopted by the Council on 28 March 2023.[112] It sets a specific overall EU-level objective of 310 Mt CO_2 equivalent of net removals in the LULUCF sector in 2030, involving binding targets at Member State level.

The revised version of the Renewable Energy Directive approved by the Council on 9 October 2023 puts emphasis on the need to avoid market distortions and adverse impacts on biodiversity in relation to using biomass as an energy source.[113] To this end, cascading use of biomass is postulated as a guiding principle, strengthening the sustainability criteria for the use of biomass for energy purposes. The use

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[105] European Commission (2020d). A new Circular Economy Action Plan - For a cleaner and more competitive Europe. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2020) 98 final.

[106] Schwind, S., Reichert, G. (2023). Packaging and packaging waste. cepPolicyBrief No.3/2023.

[107] European Commission (2023c). Proposal for a Directive of the European Parliament and of the Council amending Directive 2008/98/EC on waste. COM(2023) 420 final.

[108] European Commission (2018). A European Strategy for Plastics in a Circular Economy. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2018) 28 final.

[109] European Union (2019). Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment.

[110] European Union (2023a). Commission Regulation (EU) 2023/2055 of 25 September 2023 amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) as regards synthetic polymer microparticles.

[111] European Commission (2022c). EU policy framework on biobased, biodegradable and compostable plastics. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2022) 682 final.

[112] European Union (2023b). Regulation (EU) 2023/839 amending Regulation (EU) 2018/841 as regards the scope, simplifying the reporting and compliance rules, and setting out the targets of the Member States for 2030, and Regulation (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review.

[113] European Union (2023c). Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652.

of so-called "advanced biofuels" produced from non-food biomass is favoured, which are pragmatically defined based on a feedstock list in the annex to the revised Directive. For the transport sector, it establishes combined minimum Member State targets for the share of advanced biofuels, biogas and renewable fuels of non-biological origin (i.e. fuels based on renewable hydrogen) in the energy supplied to the transport sector (2025: 1 %, 2030: 5.5 %). Moreover, the use of bio-based fuels in aviation is specifically promoted by the ReFuelEU Aviation Regulation likewise approved on 9 October 2023.[114] It introduces an obligation for aviation fuel suppliers to ensure that minimum shares of sustainable fuels are present in all aviation fuel provided to aircraft operators, with minimum shares increasing progressively from 2025 (2 %) to 2050 (70 %). Certified biofuels are recognized to be part of this group of sustainable fuels.

Finally, independent of the Fit-for-55 package, the Communication on a Sustainable Carbon Cycles Initiative published in December 2021 also provides important impulses for the future of the bioeconomy.[115] It asks for the development and implementation of a standardized methodology for monitoring, reporting and verifying carbon gains and carbon in agricultural biomass generation. Moreover, it defines for the first time a concrete goal for replacing fossil-based resources in the production of chemicals and plastics, stating that by 2030 at least 20 % of the carbon used in the EU production of these products should stem from non-fossil sustainable resources, including sustainably generated biomass.

Thus, the Green Deal acts as an amplifier of the bioeconomy strategy in several dimensions. First, it provides additional public-private funding channels for the marketization of new bio-based technologies and associated value chains. Second, it boosts the deployment of bio-based solutions through a mix of new or enhanced regulatory incentives, from overarching reforms (e.g. reform of emissions trading, more ambitious renewable energy targets) to application-specific usage targets and quotas. Third, by differentiating the regulatory view on bio-solutions according to biomass origin, cultivation practices and end-of-life fate, it further underpins the central importance of sustainability and circularity as governing principles for the formation of future supply chains.

In its 2022 review of the bioeconomy strategy, the Commission identified overall progress in the development of the EU bioeconomy under the premises of the Green Deal, especially concerning public and private investments in research and innovation.[116] At the same time, it pointed out specific challenges for bio-based supply chains that remain to be addressed, some of which have been exacerbated by recent political developments (Ukraine war, supply chain disruptions, general geopolitical situation) and their impact on the EU's overall strategy (resilience as a political paradigm). The first challenge lies in the increased technological restrictions on biomass cultivation. In order to comply with the sustainability objectives of the Green Deal, the LULUCF sector must in the future take even greater account of the ecological boundaries in land management and at the same time gear land use towards a positive contribution to the greenhouse gas balance (carbon farming practices) and climate change adaptation. This creates technological pressure to adapt and a corresponding need for investment which is exacerbated by the second challenge, i.e. a growing demand for domestic biomass. This arises both from the growth of bio-based applications in industry and the increasing need

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[114] European Union (2023d). Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation).

[115] European Commission (2021). Sustainable Carbon Cycles. Communication from the Commission to the European Parliament and the Council. (2021) 800 final.

[116] See European Commission (2022a).

for security of supply in the area of basic needs (food, energy). The third challenge is seen in restrictions on access by industry stakeholders to further key resources: the availability of a skilled workforce and of capital for the commercialization phase of biotech innovations (see Subsection 2.4).

5 Policy implications

5.1 Fields of action

The preceding discussion paints a clear picture of the role of the bioeconomy in the EU's long-term industrial strategy. The diversity of innovative bio-based supply chains is not only an important asset for maintaining competitiveness and innovative capacity in the post-fossil age. If managed wisely, they can also make a real contribution to the goals of security of supply, circularity of resource use and market penetration of sustainable agricultural methods. However, a focused and market-oriented regulatory approach is required to leverage this potential. **The aim must be to remove barriers to the exploitation of scale economies in sustainable bio-based technologies and thus create the conditions for truly fair competition with established business models**. This is an extremely complex task. Our analysis has shown that the development of new bio-based supply chains faces barriers at all levels. Overcoming these requires a whole bundle of diverse measures. The inherent stability of established agglomeration structures (see Subsection 2.3) imposes additional restrictions on regional policy initiatives.

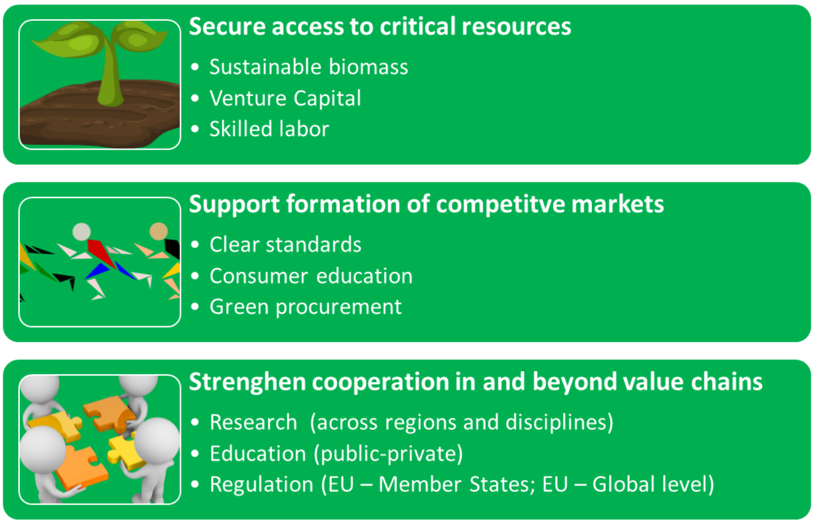
First and foremost, a consistent overarching policy approach at EU and Member State level is needed to overcome the fragmentation of the regulatory landscape. It must be based on a clear vision of a sustainable EU bioeconomy that is consistently applied in all policy projects. This should involve an integrated supply chain perspective, assessing both economic and ecological impacts from a life cycle perspective. At the same time, the architecture of supply chains must be regarded as dynamic. Maintaining their contribution to value creation requires persistent product and process innovation. **This can only succeed if Europe achieves global leadership at all stages of the innovation process - from basic research to commercialization.**

Under the umbrella of such a concept of bioeconomy policy, concrete fields of action must be developed that translate the vision of the future into a consistent target-instruments relationship. Based on the foregoing core results, we identify three fields of action (see Figure 16). **The first field highlights the resource perspective**. Domestic bio-based supply chains can only thrive if access to critical inputs is guaranteed. This applies not only to sustainably generated biomass as a key raw material. Equally important for the implementation and upscaling of business models is the availability of venture capital and adequately qualified workers.

The second field is market development. To at least partially compensate for the competitive disadvantages of sustainable, but early-stage bio-based solutions under the current market structures, regulatory market segmentation could be the right strategy. However, it must be carefully balanced against the need to avoid unbearable cost burdens for consumers and downstream industries. Strengthening market signals by improving the flow of information is of crucial importance.

The third field is the expansion of cooperation networks within and between value chains. Mastering the technological complexity of processes and their social side effects requires continuous exchange. A policy that promotes the formation of stable cooperation networks can contribute to the robustness of domestic value chains and - as our empirical analysis suggests - even increase the capacity for innovation. This is not just about promoting cooperation between private actors. Some networks require the active involvement of actors from the political sphere, such as the need for regulatory cooperation within the EU and at the global level.

Figure 16: Key fields of policy action for the EU bioeconomy



Secure access to critical resources

- Sustainable biomass
- Venture Capital
- Skilled labor

Support formation of competitve markets

- Clear standards
- Consumer education
- Green procurement

Strenghen cooperation in and beyond value chains

- Research (across regions and disciplines)
- Education (public-private)
- Regulation (EU – Member States; EU – Global level)

Source: own illustration

5.2 Recommendations

Turning the strategic fields into concrete policy action requires the EU to address all stages of bio-based value chains. In the following, we make concrete proposals for instruments to tackle specific barriers that exist at specific stages of the value chain (see overview in Figure 17).

- **Enhance skill supply:** Shortages in the supply of young talent and experienced professionals for biotech research and manufacturing must be overcome in a targeted manner. An important step is the expansion of university study programs that are closely tailored to the needs of an industry that is strongly research based. Specialized master’s degree programs that involve an intensive exchange with local manufacturing companies can lay the foundation for regional "talent factories", overcoming the problems of finding the right matches on local labour markets, and providing companies with a reliable flow of highly qualified workers. At the same time, support for upskilling and reskilling of the existing workforce needs to be expanded. Specialized training centres that focus on the practical skills that are lacking (e.g. laboratory skills) can reduce the overall costs of retraining which arise from the structural change brought about by economies of scale. It makes sense to organize these centres as public-private partnerships, to cope with the risk of underinvestment on the company side (generation of positive externalities). In addition, this gives regions an influence over training content and enables them to create better coherence with the regional economic development strategy. For the recruitment of skilled workers from non-EU countries, global recruitment campaigns are needed that convey the advantages of working and living in the EU. In the future, these should culminate in greater harmonization of high-skilled immigration policies, including common support programs for organizing the move to Europe.

- **Boost venture capital financing:** Access to venture capital is a decisive factor for the commercialization of biotech innovations in the form of start-ups and their upscaling (see Subsection 2.4). It can be significantly improved through partial state coverage of return risks, by providing credit guarantees or equity. In the long term, this will also help to strengthen the private venture capital culture in Europe. The EU should expand existing financing channels in a targeted manner under the umbrella of the Green Deal Investment Plan. EIB investments in privately managed venture capital funds supported by experienced industry players are a suitable means of ensuring the targeted use of funds. To avoid conflicts with the other objectives of the Green Deal (see Subsection 4.2), transparent sustainability requirements must be defined for potential investment projects, particularly with regard to the origin of biomass and the existence of recycling channels. The Circular Bioeconomy Fund is a role model for this (see Subsection 4.1) and should be continuously expanded. In addition, Member States should examine options for targeted tax policy incentives for venture capital (e.g. treatment of loss carryforwards in the event of a change of shareholder) within their national tax systems.
- **Promote research cooperation:** Recent empirical analysis points to the great importance of cooperation for the efficiency of research efforts, both in general and specifically for the bioeconomy sector (see Section 3). For the bioeconomy, as a cross-sectoral segment that draws on many fields of technology and knowledge channels, cooperation in research always has several dimensions. It includes cooperation between biotech clusters in different regions and Member States as well as cooperation between institutions (companies, private research institutions, universities) and disciplines (natural sciences, engineering, mathematics, etc.). In view of the competition with biotech nations that are strong on research, such as the USA, Japan and South Korea (see Subsection 3.2), Europe should join forces and tap into cooperation potential in all dimensions. Therefore, an important task of EU R&D policies is to stimulate research cooperation at all levels. Against this background, the targeted promotion of problem-oriented, interdisciplinary and international research via the EU research framework program Horizon Europe is the right approach. In the future, however, it should be accompanied even more strongly by evaluation measures. These should not be limited to immediate research outcomes (e.g. patenting measures) but should encompass all stages of the innovation chain up to the successful upscaling of new business solutions resulting from R&D projects.
- **Extend environmental monitoring: I**nnovative bio-based solutions will only be able to compensate for cost disadvantages on markets if confidence in the sustainability of their supply chains is widespread. This requires the monitoring and documentation of environmental life-cycle impacts. The extraction of the biomass used is a particularly critical step, not only with regard to the overall GHG balance, but also with regard to possible local environmental effects of land management, such as biodiversity impacts and the role of indirect land use change (see Subsection 2.4). In this respect, the EU can contribute to overcoming information gaps and asymmetries by developing a standardized methodology and an associated certification framework (see e.g. the current legislation on the certification of carbon removals). At the same time, the diversity of products and their potential environmental effects undoubtedly represents a major challenge which requires close cooperation between regulators, certification bodies and industry stakeholders.
- **Create innovation-friendly market environment:** To create investment incentives for the development of sustainable solutions (e.g. switch to second- or third-generation biological feedstocks), the prospect of long-term compensation for high development costs must be offered.

At the same time, the steering effect of demand through price mechanisms must be maintained. This calls for market segmentation in order to achieve higher equilibrium prices for sustainably generated bio-based products. From the consumer's point of view, its first prerequisite is transparent product differentiation. The aforementioned certification framework can be used as a basis for product labels. In addition to creating transparency, the development of such a market segment can be directly supported by demand-side policies, e.g., through specific rules for green public procurement. The difficulty lies in reconciling sustainability principles with the general objectives of cost-efficient and competitive public procurement. The debate on similar regulations in the Net Zero Industry Act can provide experience in this regard.[117] Finally, the concept of regulatory sandboxes, which has already been tried and tested in other technology fields (e.g. hydrogen), can be applied to the trial phase of innovative biotechnologies to test their viability in a customized market environment (e.g. waiving of certain technical process requirements).

- **Promote R&D in recycling of bio-based plastics and food waste:** Bio-based solutions can only contribute to the creation of sustainable supply chains if they offer options for the economic recycling of end products. In some segments of the bioeconomy, such as bio-based plastics, high costs are currently still preventing the growth of recycling capacities (see Subsection 2.4). Research and testing of methods to increase the material and energy efficiency of recycling processes should therefore be consistently promoted. This will also benefit the environmental balance and thus the sustainability image of the products. Moreover, the development of supply chains for the utilization of food waste beyond the food industry should be promoted, to provide innovative waste-based feedstock solutions with a stable resource base for the market ramp-up.
- **Establish overarching guidelines:** The various components of a supply chain-oriented policy strategy require centralized control through a monitoring system. As with existing strategies for the promotion of renewable energies or the domestic supply of critical raw materials, quantitative targets should serve as the yardstick. In the interests of technology openness, these should not be limited exclusively to the production of bio-based products. Instead, binding targets should focus on reducing the use of fossil feedstocks, e.g., in the production of chemicals and plastics. As alternatives or supplements to bio-based solutions, the use of renewable hydrogen or recycled CO_2 should also be acknowledged for achieving these targets. The Commission has already formulated such targets in its Sustainable Carbon Cycles Initiative (see Subsection 4.2), but only at an EU-wide level and in a legally non-binding form. If these were translated into binding targets at Member State level, it could provide the basis for an obligation for each Member State to take appropriate national measures. Of course, the level of the target and its timeframe should be chosen realistically. Moreover, the EU should work towards strengthening the global governance of bio-based industries to guarantee a level playing field for the European bioeconomy on international markets. This will involve efforts to harmonize sustainability criteria, but also concrete global action plans such as the current negotiations on a UN treaty against plastic pollution.[118]

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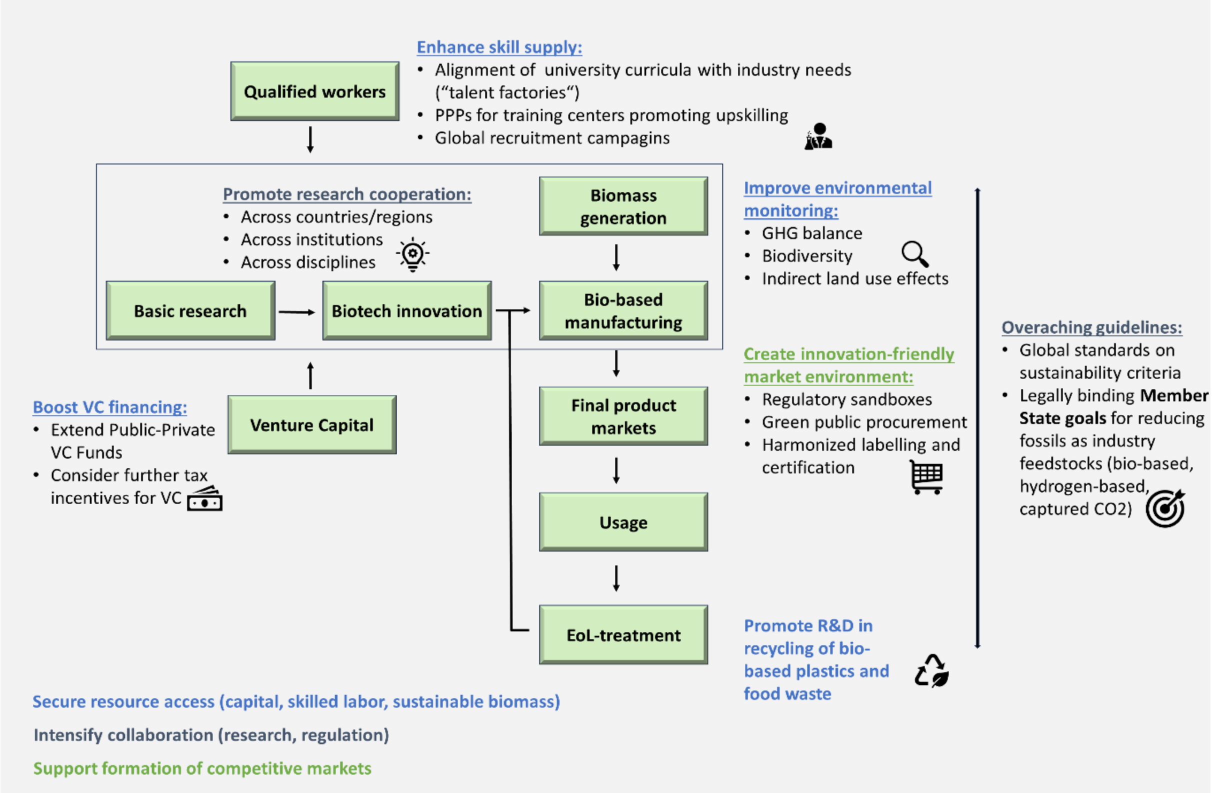
[117] European Commission (2023d). Proposal for a Regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act) (COM(2023) 161 final).

[118] UNEP (2022). Intergovernmental Negotiating Committee on Plastic Pollution. United Nations Environment Programme.

Figure 17: Recommendations for policy actions along bio-based value chains



Source: own illustration

6 Conclusion

Securing the long-term competitiveness of a rapidly transforming European industrial base will be one of the main challenges for the EU in the coming years. The multitude of interdependent global risks requires green diversification to become a core principle of any industrial strategy. The bioeconomy, an umbrella term for value chains based on the use of biological resources, has the as yet untapped potential to become a central pillar of the EU Green Deal. Beyond traditional usage channels, bio-based applications have long since penetrated into segments such as the production of basic chemicals, plastics and fuels. By replacing finite raw materials with renewable ones, they not only reduce the carbon footprint of industrial supply chains. They also contribute to reducing dependence on the external supply of fossil fuels and, through the utilization of biogenic waste and agricultural residues as feedstocks, create additional options for closed-loop material cycles supporting overall resource efficiency.

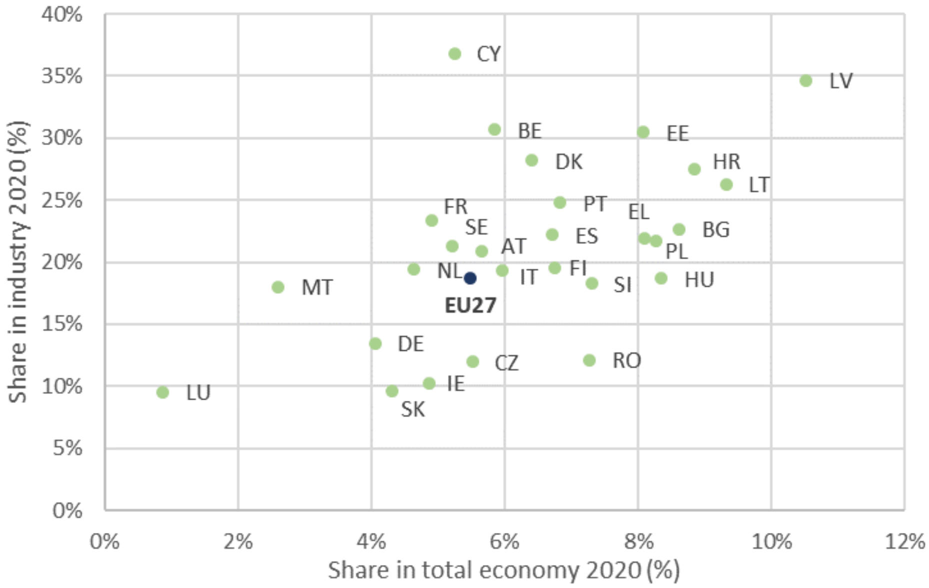
At the same time, however, the bio-based segment of European manufacturing faces multiple growth barriers. Some of these are of an overarching nature. Due to long development phases and the high knowledge intensity of production, the increasing scarcity of specialized skilled labour and the low liquidity of venture capital markets in the EU represent particularly severe constraints on emerging biotech solutions. In addition, some bio-based segments face supply-chain-specific challenges concerning the sustainability of biomass extraction and the heterogeneity of product properties, suggesting a high need for information on the part of users. In addition to overcoming domestic obstacles to market growth, Europe must hold its position in the global innovation race for biotechnologies in order to secure new value creation potential through technological leadership. In this respect, our analysis of global patent data shows that, despite some impressive recent breakthrough innovations, the EU has lost ground in quantitative terms to global competitors like China and the USA. Policymakers should take action based on a careful monitoring of the success factors behind highly innovative regions. Our empirical analysis of the determinants of biotech innovation shows that research-strong biotech clusters in the EU tend to have some features in common: an abundance of human resources in science and technology, an overall high level of education among the population and a high degree of supra-regional research cooperation. In view of the strong agglomeration economies, policy efforts to enhance the overall biotech innovation potential should focus on expanding these region-specific strengths.

In sum, unleashing the growth potential of the bioeconomy against this multitude of challenges requires a value chain-oriented strategy, addressing barriers from the early development stages up to final product markets. Classic EU policy instruments like financial support to basic research and creation of stakeholder platforms must be complemented by targeted and coordinated actions along all relevant stages of bio-based value chains. This cepInput proposes three fields of action as future cornerstones of such an holistic strategy. The first field consists of eliminating barriers to resource access, focusing on the critical supply bottlenecks of venture capital, skilled labour and sustainable biomass. The second field is focused on market formation, ensuring a level playing field for bio-based solutions that recognizes their critical role for the Green Deal. The third field aims at strengthening stakeholder cooperation. This concerns both the promotion of cooperation in research across regions, disciplines and institutions, and regulatory cooperation between the EU and Member States.

The set of instruments proposed stresses the need to escape the classic logic of passive subsidization. Instead, policy processes need to take the form of an active and continuous engagement with industry stakeholders, addressing technology-specific barriers to market formation through common initiatives (e.g. PPPs, Public-Private Venture Capital Funding) and knowledge exchange. Such an intricate approach requires guiding principles. In this respect, the EU target systems established for emission reductions and most recently critical raw materials represent a suitable role model for bioeconomy policies. Ambitious but realistic Member State targets for replacing fossil-based industry feedstocks with sustainable alternatives (including, but not limited to sustainable bio-based solutions) are the right step in this direction. Simultaneously, the EU must use its full weight in the international arena to enforce standards for a fair competitive environment for bio-based solutions on global markets.

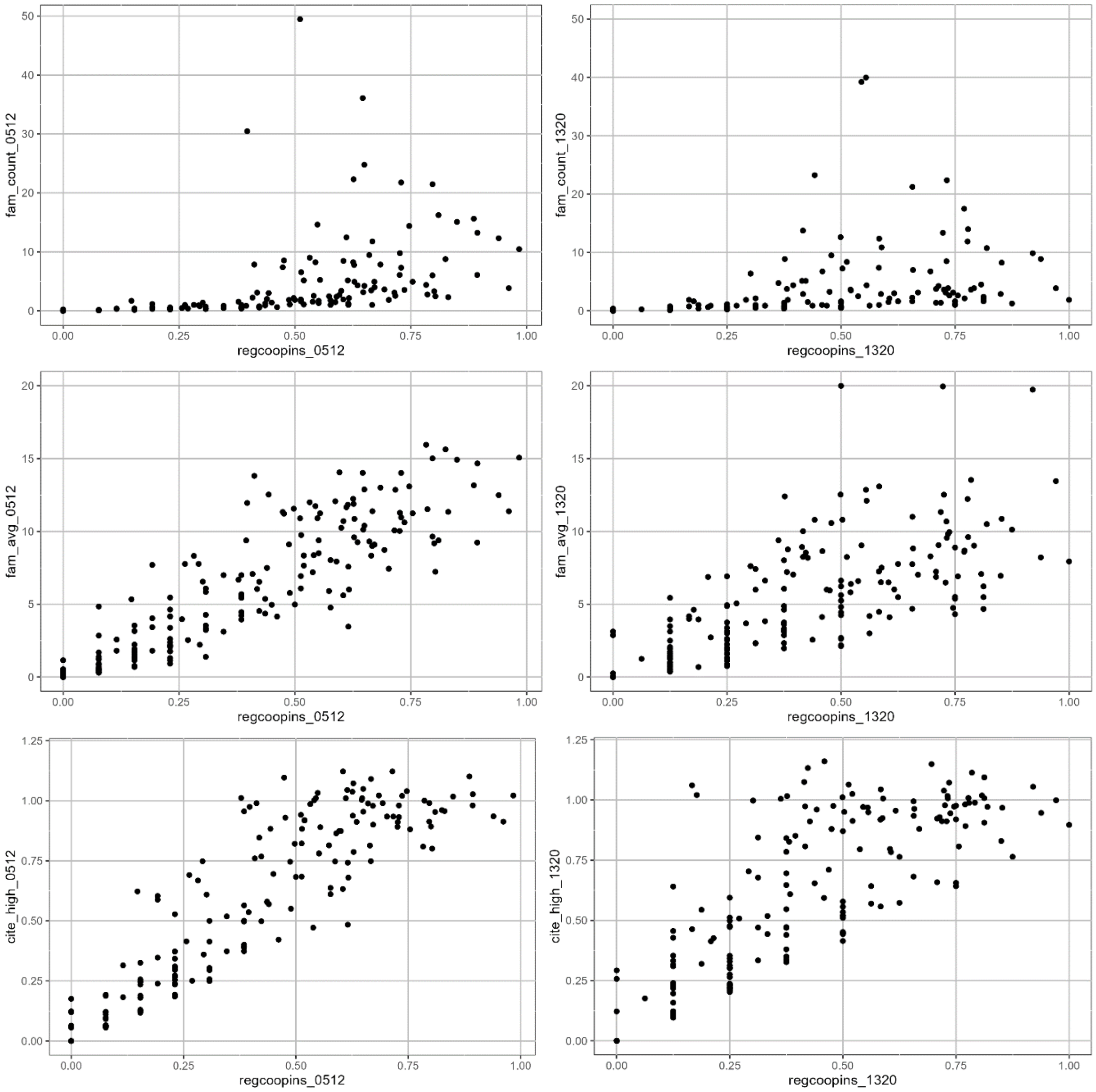
7 Appendix

Figure A 1: Share of the bioeconomy in national value added 2020 by Member State



Source: JRC (2024); own calculations.

Figure A 2: Innovation performance measures and cross-regional cooperation intensity



Sources: EPO (2024); OECD (2024b); own calculations.

Table A 1: Determinants of regional biotech innovation – Tobit regression results model 1

				Dependent variables					
	fam_count			**fam_avg**			**cite_count**		
	Estimate	*Std. Error*	*p-Value*	*Estimate*	*Std. Error*	*p-Value*	*Estimate*	*Std. Error*	*p-Value*
Regressors									
intercept	-1.0369	0.2409	0.000016***	-0.9119	0.3302	0.005747**	-0.5583	0.2783	0.044810*
inv_count (lag)	0.5927	0.0178	<0.000001***	0.0564	0.0188	0.002630**	-0.0163	0.0153	0.286059
HRST (lag)	0.5560	0.0471	<0.000001***	0.2494	0.0579	0.000017***	0.3011	0.0485	<0.000001***
tert_ed (lag)	0.5476	0.2117	0.009685**	1.1513	0.2807	0.000041***	1.2518	0.2335	<0.000001***
GDP_pc (lag)	0.1751	0.1553	0.259306	0.4256	0.2067	0.039516*	0.1190	0.1730	0.491616
reg_coopins (lag)	0.4072	0.0764	<0.000001***	0.9480	0.1078	<0.000001***	0.8610	0.0925	<0.000001***
tech_coopins (lag)	0.0162	0.2420	0.946766	0.0910	0.3426	0.790588	0.3141	0.3036	0.300983
R^2 Cox-Snell	0.772			0.521			0.527		
No. observations	2212			2212			2212		

Sources: EPO (2024); OECD (2024b); Eurostat (2024c); own calculations. Significance codes: 0.001 '***' 0.01 '**' 0.05 '*'

Table A 2: Determinants of regional biotech innovation – Tobit regression results model 2

				Dependent variables					
	fam_count			**fam_avg**			**cite_count**		
	Estimate	*Std. Error*	*p-Value*	*Estimate*	*Std. Error*	*p-Value*	*Estimate*	*Std. Error*	*p-Value*
Regressors									
intercept	0.3319	0.1507	0.027661*	-0.0047	0.2742	0.986365	0.3368	0.2050	0.100390
inv_count (lag)	0.1273	0.0152	<0.000001***	-0.0028	0.0233	0.903852	-0.0334	0.0168	0.047005*
HRST (lag)	0.2055	0.0297	<0.000001***	0.1272	0.0494	0.010040*	0.1931	0.0357	<0.000001***
tert_ed (lag)	-1.0059	0.1383	<0.000001***	-0.8417	0.2477	0.000679***	-0.6048	0.1814	0.000856***
tert_ed (lag) X inv_count (lag)	0.48130	0.0118	<0.000001***	0.0755	0.0174	0.0000142***	0.0461	0.0125	0.000234***
GDP_pc (lag)	-0.0450	0.0947	0.635044	0.2590	0.1704	0.128532	-0.0470	0.1250	0.706722
reg_coopins (lag)	0.2589	0.0482	<0.000001***	0.4705	0.0899	<0.000001***	0.3075	0.0645	<0.000001***
tert_ed (lag) X reg_coopins (lag)	1.2455	0.0500	<0.000001***	2.6592	0.0915	<0.000001***	2.4138	0.0654	<0.000001***
tech_coopins (lag)	0.1109	0.1570	0.480136	0.0983	0.2800	0.725594	0.1944	0.2031	0.338318
R^2 Cox-Snell	0.890			0.686			0.723		
No. observations	2212			2212			2212		

Sources: EPO (2024); OECD (2024b); Eurostat (2024c); own calculations. Significance codes: 0.001 '***' 0.01 '**' 0.05 '*'

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