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National specialization and diversification in the bioeconomy: Insights from biobased technologies in chemical and pharmaceutical sectors

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ABSTRACT

Facilitating the transformation of innovation systems is a vital endeavor within the global quest to diminish the detrimental environmental consequences of economic activities. Against this background, scholars and policymakers emphasize the potentials of a societal transition towards a ‘bioeconomy’. In this paper, we study the technological specialization of countries in biobased technologies relating to chemicals and pharmaceuticals, which are key constituents for a future bioeconomy. By identifying these technologies in patent and publication data, we analyse specialization and diversification processes for 15 countries from 1997 to 2019. We find that countries that already had a relative advantage in biobased technologies are more likely to develop new specializations in technologies that relate to the bioeconomy. Beyond that, countries’ specialization in biobased technologies varies between basic research (scientific publications) and applied research (patents). Our study also shows that greater technological complexity tends to limit specialization in biobased publications, highlighting the need for targeted policy interventions supporting the bioeconomy.

1. Introduction

The major environmental issues associated with climate change pose significant challenges to countries worldwide: health risks, declining biodiversity, emerging conflict potential, and decreasing agricultural production [1]. New technologies can help to limit the negative impacts of climate change, and political regulation can support their development [2–4]. Therefore, there is a need to study the structures and transition processes involved in the emergence of sustainable technologies. In fact, many countries aim to create structures to accelerate sustainability transition processes, which set the foundation to limit environmental problems in the future, for example by promoting and using technologies with lower resource consumption or lower CO_2 emissions [4,5].

Against this background, the *bioeconomy* can be considered to be a particular important cornerstone of more sustainable economies [6,7].[1] The bioeconomy refers to an economic system that utilizes biological resources and processes to generate sustainable and renewable products, energy, and services. It encompasses a wide range of sectors, including agriculture, forestry, fisheries, food production, biofuels, bioplastics, biomaterials, and biotechnology. A transformation towards a future bioeconomy strongly relies on innovation and technological progress [8]. In contrast to conventional technologies, biobased technologies aim to contribute to sustainability transition processes and can drive sustainable economic development [7,9]. Recognizing these opportunities, single countries as well as the European Union have developed bioeconomy strategies that aim at supporting biobased innovation [10,11]. However, the emergence of new biobased technologies is barely researched in the existing literature, in contrast to other types of sustainable technologies [12,13]. One of the challenges in studying the bioeconomy is the limited availability of data. The bioeconomy encompasses multiple sectors that cannot be adequately captured using conventional data sources on economic activities or innovation endeavors [14,15]. Existing attempts to estimate the contributions of the bioeconomy to specific sectors often rely heavily on assumptions due to the complexity of accurately determining its shares in sectoral activities [16,17]. Developing novel approaches to measure the emergence of new biobased technologies and comparing the progress in different regions

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[1] It is important to acknowledge that the bioeconomy does not inherently guarantee sustainability and may introduce new environmental and social challenges [95]. Our paper does not intend to explore the sustainability effects of the bioeconomy.

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globally, therefore, poses a significant research gap [9,18]. Although research interest in the bioeconomy has grown exponentially in recent years [19,20], previous studies on bioeconomy innovations have mostly focused on analyzing biotechnology, thus neglecting progress in biobased innovation in other sectors [21,22].

To address this research gap, our study delves into national innovation systems within the bioeconomy, examining the factors that drive national specialization and diversification in biobased technologies. In doing so, we aim to provide valuable insights by answering the following research question: *To what extent are countries specializing and diversifying into new biobased technologies and which factors drive these processes?*

Our paper specifically centers on biobased technologies within the chemical and pharmaceutical sectors. These sectors hold immense potential in driving sustainability transitions towards a bioeconomy and establishing new benchmarks for the development of a wide range of biobased products [7,18,23]. As a consequence, the development and adoption of biobased technologies in the chemical and pharmaceutical sectors can significantly reduce the negative environmental impacts associated with economic activities in various industries. In our empirical analysis, we do not assert a complete representation of the bioeconomy and its associated technologies. Rather, our study concentrates on specific sectors that, while not exhaustive, represent significant pillars of technological progress within the bioeconomy. By focusing on these sectors, our paper seeks to contribute to the acceleration of sustainability transitions and the overall advancement of the bioeconomy.[2] From an empirical perspective, we identify bioplastics, biopharmaceuticals, biotechnology and biobased detergents in publication and patent data and follow a standard research design for the analysis of specialization and diversification processes often used in economic geography [12,24]. Our data set covers a panel of 15 countries over the period 1997–2019, enabling us to analyse specialization and diversification in biobased technologies.

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature on innovation in the bioeconomy, on innovation systems and on specialization in new (sustainable) technologies. We present our empirical approach in section 3. Section 4 discusses the results, while section 5 provides a conclusion as well as policy implications.

2. Literature review and theoretical foundations

2.1. Innovation in the bioeconomy

The bioeconomy plays a pivotal role in the global endeavor to develop innovative and sustainable technologies that address pressing environmental challenges [6,7,25]. In the context of this study, we build on a bioeconomy definition of the European Commission (EC) [26,27].

The bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles.

For the empirical section of this paper, however, we will deviate from this definition and concentrate on biobased technological innovations in the chemical and pharmaceutical sectors. This approach will allow us to capture only a subset of all innovative activities in the bioeconomy. Generally speaking, there is no universal definition of the bioeconomy, which is why research results on the bioeconomy depend very much on the conditions, criteria and assumptions under which the bioeconomy is defined [14,17,28]. There are innovations that are considered to be part of the bioeconomy and are renewable, but trigger new direct conflicts e.g. with the use of natural resources or ecosystems. Therefore, biobased technologies are not necessarily sustainable solutions that mitigate negative environmental impacts [29]. Moreover, reproduced imaginaries of the bioeconomy often fail to consider the consequences for sustainability [30,31]. The multifaceted nature of the bioeconomy is illustrated by different perspectives, primarily centered on different emphases on technology, ecology or resource use. This divergence of viewpoints, referred to as “bioeconomy visions” as identified by [32] highlights a notable dichotomy. Moreover, emerging narratives around the notion of the bioeconomy have changed expectations of bioeconomic innovation [31]. In particular, discussions around drop-in and functional innovations in the bioeconomy illustrate the wide range of perspectives and understandings [33,34]. Our approach is based on the understanding of [29] that bioeconomy innovations range from substitutes to new behavior, causing differences in both the ecological and the disruptive potential for sustainability transitions [9]. However, there are other developments impacting bioeconomic innovations across sectors. In general, innovation systems for the development of biobased technologies are more complex and feature high levels of uncertainty in many industries [35]. Moreover, knowledge, scientific research and innovation play a key role in driving the bioeconomy [7,8], which highlights that biobased technologies often follow a STI (science, technology, innovation) mode of innovation and learning [36].

Even though innovation is pivotal for the progress towards a future bioeconomy, methodological issues in measuring and monitoring biobased innovation have not received much attention in the literature. In fact, previous studies have focused on developing indicators to quantify the economic effects of the bioeconomy, finding an overall increase in bioeconomy activities in many countries and regions [16,17]. However, a large number of these studies struggle methodologically in clearly distinguishing between bioeconomy and non-bioeconomy activities, as standard classifications of economic activities fail to capture the bioeconomy. In the literature, there are approaches to more precisely delineate biobased technologies or economic activities of the bioeconomy. However, there is a lack of comprehensive data in most areas [14,15,18,37]. The same applies to other attempts, such as the study of the impact of the bioeconomy on the national economy of individual countries [16,38]. These approaches are often limited because the existence and progress of bioeconomic activities are not yet measurable [14,18]. It is crucial to recognize, as suggested by [28] that the bioeconomy extends beyond the biobased substitution of environmentally harmful goods, encompassing transformative biotechnological innovations [9].

The current state of research is largely based on the discussion of which of the new biobased technologies contribute to sustainable development (ecological perspective), and how the use of biobased innovations can contribute to economic growth (resource use). In line with the terminology of [32] there is a lack of technological perspectives in previous studies that investigate the knowledge-intensive technological developments of the bioeconomy, especially in terms of research, application, and the associated diversification and specialization processes in different countries. At the same time, there is a growing interest in studies that aim to analyse impacts of the bioeconomy and to establish criteria for measuring innovation progress [9,18,39]. This observation is accompanied by the recognition that, within certain sectors of the bioeconomy, a clear distinction between biobased technologies and non-biobased technologies is needed. Such a distinction could enable a targeted examination of the developmental patterns of biobased technologies and the transition processes towards a future bioeconomy. In this paper, we contribute to resolving these research gaps.

2.2. National specialization and diversification in sustainable technologies

The development of new technologies is driven by existing innovation capabilities, which determine the ability of countries to gain

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[2] Please note, biopharmaceuticals are not included in some of the bioeconomy strategies around the world, however, from a technology viewpoint this is a key sector of biotechnological progress based on living cells or parts thereof.

competitive advantages in certain technology fields [40]. Against this background, gaining competitive advantages in sustainable technology fields (e.g. renewable energy, waste management, biobased technologies) is a dedicated goal of many nations. Countries can lead certain markets, act as early adopters of new technologies, and drive the emergence and global diffusion of sustainable innovations [41]. At the same time, "green windows of opportunity" [42] offer latecomer countries possibilities for technological catch-up. In light of this, the concept of national innovation systems (NIS) is well suited to study the extent to which countries are able to develop new technologies and to establish competitive advantages in certain technological fields [43,44]. Here, these systems refer to the various institutions, policies, and actors that shape the national context in which innovations emerge. In particular, the latter include research institutes, universities, private firms, and funding agencies [44,45]. The interaction of these actors creates an environment that either supports or hinders the development of new technologies [44]. In the more recent literature on innovation systems, there is a growing concern about how to steer the directionality of these systems to enable sustainability transformations. Consequently, researchers have, for example, delved into the concepts of transformative knowledge and transformative innovation [46]. The transformation of innovation systems requires a more advanced understanding to address all the dimensions that arise with sustainability issues of innovation. Particularly in the case of the bioeconomy, social and ethical consideration influence what [47] describes as the dedication to transforming innovation systems. When examining innovation systems and the emergence of new technologies, it becomes evident that certain countries excel in diversifying and specializing within specific industries, while others struggle to create an enabling environment to support the development of innovative technologies [24]. While there is a rich literature on these issues for many types of sustainable technologies [12,48], there is a lack of empirical studies on the specific case of biobased technologies [49,50].

In light of this, we draw upon the existing literature on national specializations in sustainable technologies (broadly defined) and utilize the insights gained from these studies to formulate hypotheses. These hypotheses are then empirically tested in the specific case examined in this paper: biobased technologies within the chemicals and pharmaceuticals sectors. We follow the empirical approach of [12] who examined national specialization[3] and diversification processes in sustainable technologies. They find that national specialization and diversification in sustainable technologies are primarily related to the respective phase in the technology life cycles. At the same time, they find that technologically leading countries are more likely to develop specializations in sustainable technologies. In that regard, a high degree of technological complexity also does not prove to be an obstacle for national specializations [12]. In previous studies, complexity was predominantly shown to be an inhibiting factor for diversification [51,52]. Furthermore, it is important to note that new sustainable technologies are often in the early stages of their life cycle, and their development demands a significant amount of tacit knowledge [48]. However, knowledge capabilities are partly complementary to non-sustainable technologies [53].

The utilization of new sustainable technologies has the potential to make a substantial contribution to mitigating the impacts of climate change. However, it is crucial to recognize that realizing this potential requires concurrent systemic adjustments on the part of policy-makers. Such adjustments are necessary to fully harness the existing potential of these technologies [4,12,44]. Previous research shows that innovation systems have so far shown some weaknesses in promoting new sustainable technologies [2]. Here, policy intervention can correct system failures and help to positively influence sustainable technology development [54]. In particular, stringent environmental policies are able to evoke innovations that aim at reducing emissions and other environmental burden [3].

Based on the explained state of research on sustainable technologies, this paper examines national specialization and diversification in biobased technologies. For this purpose, the chemical and pharmaceutical sectors are important technology fields, as there is a global relevance due to their high transformational potential for the bioeconomy and considerable investments of companies in these sectors [7,23]. This is worth mentioning because other technologies in the bioeconomy are not yet as widely applicable, investments and other resources are still lacking, and, from a methodological perspective, a quantitative approach for identifying these technologies is hardly possible [15,55,56]. In addition to that, the overall progress of the bioeconomy is mainly based on research and innovation in pharmaceuticals and biotechnology fields [7,8,23].

The following hypotheses for the specialization and diversification of countries in new biobased technologies in the chemical and pharmaceuticals sectors can be derived from the outlined research on innovation in the bioeconomy (see Section 2.1) combined with the literature on sustainable technologies presented above. A key finding from analyzing sustainable technologies is the associated high technological complexity compared to conventional technologies, which might pose barriers for new specializations.

H_1. *High technological complexity inhibits national specialization in complex biobased technologies.*

Similar to the state of research on sustainable technologies, we assume that there are high technological entry barriers to the development of biobased technologies. For this reason, countries that develop a relative advantage in a particular technology are primarily those that have previously specialized in that technology, meaning that technological specialization is a path-dependent process.

H_2. *Countries that do not specialize in a certain biobased technology are less likely to develop new specializations in this biobased technology, while countries that are specialized in a given biobased technology are likely to maintain this specialization over time.*

Because of the important role of policy in overcoming market and system failures in the development of sustainable technologies, we assume that stringent environmental policy has a positive impact on the extent to which individual countries specialize in biobased technologies.

H_3. *Stringent environmental policy has a positive impact on the national specialization in biobased technologies.*

3. Data and methods

3.1. Using patent and publication data for measuring innovation in the bioeconomy

The research design in this paper is primarily based on patent data, as it has proven to be a suitable indicator for measuring technological progress (in sustainable technologies) [12,48,52,57,58]. Patents are an essential data source for mapping inventions [59,60]. However, not all inventions are patentable and some are protected by other means such as secrecy [59]. Moreover, the propensity to apply for patents varies greatly between different industries and not all inventions are actual innovations that are introduced to the market [60]. Nevertheless, it is the best possible approach to map technological transformation and new innovations [59]. This seems to be particularly appropriate for biobased technologies, as patents in these fields are the most important way of protecting intellectual property and novel knowledge [23,61].

Basic research and scientific progress are an important part of the

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[3] Countries' specialization refers to the theoretical concept of the comparative advantage of individual countries in developing new technological innovations relative to other countries and other technologies [96]. Diversification refers to the situation where countries develop new specializations over time.

innovation process in that regard and can be measured by publication data, complementing patent data for the measurement of innovation activities [62]. Publication data is a particular important proxy for innovation in biobased fields, given that these fields rely on analytical knowledge bases that are codifiable [43].

In order to identify biobased innovations in patent and publication data, we rely on a unique empirical approach that was developed in the context of the Symobio 2.0 project at Fraunhofer ISI in Germany. For the patents, the identification of biobased technologies is based on IPC codes, whereas the identification for publications is based on keywords used in the selected IPC classes. On this basis, patent and publication data from four biobased technology groups in chemicals and pharmaceuticals are obtained.[4] The classification of the biobased technology groups is based on the definitions provided in Table 1, which are in line with previous studies. It has to be remarked that the attribution of pharmaceuticals to the bioeconomy is controversial. While the EC strategy explicitly excludes medical biotechnology, biopharmaceuticals principally fit the definition and are included in measurement frameworks by the EC [17]. Moreover, the bioeconomy accelerates opportunities for progress in pharmaceuticals, with COVID-19 vaccines being a prominent example [7,63]. Overall, our selected technology groups relate to fields, that are especially driven by biotechnological developments, while the use of large amounts of biomass is less important for these fields, with the exception of bioplastics. We provide further information on the state of research and the contribution to sustainability for all technology groups in Appendix B.

From a variety of definitions for bioplastics [69], we include plastics which are based on plants and at least in part produced from renewable biomass as a feedstock. These are not always biodegradable, while in some other definitions of bioplastics, biodegradation is used as a crucial defining feature [64,65]. The extent to which biodegradability is desirable in terms of sustainability depends on the context of each application [64,70]. The methodological classification is based on the chosen definition in combination with existing studies that have already classified and analyzed patents and publications of bioplastics[5] [71,72].

Table 1
Bioeconomy in chemicals and pharmaceuticals: definition of biobased technology groups.

Technology Group	Definition	Source
Bioplastics	Plastics produced from renewable biomass as feedstock.	[64,65]
Biopharmaceuticals	Pharmaceuticals made from biobased feedstock.	[66,63]
Biotechnology	"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."	[67; p. 9]
Biobased detergents	Detergents based on substances of animal or plant origin.	[68]

Biopharmaceuticals are drugs made from living resources, partly by employing biotechnological processes [66,63]. This slightly overlaps with the biotechnology group in cases where the innovation involves a combination with the preparation of medical purposes especially through genetic engineering [63,73,74]. Classification of patent and publication data allows to separate between the technology groups and avoids distorting effects [75]. In addition, there are several approaches of classifying biopharmaceuticals in patents and publications, which form the basis for our classification [74,75].

Biotechnology is considered a key element for the progress of the bioeconomy and, as can be seen in Table 1 and is usually classified based on the [67] definition [21,37], which is the basis for this study, since the definition also provides biotechnology patent classes [76].

The fourth investigated technology group of the bioeconomy in chemicals and pharmaceuticals are biobased detergents, which are based on substances with animal or plant origin [68]. Our classification is based on the IPC class C12N, which is consistent with the aforementioned definition and suitable to identify biobased detergents in patent data[6] [77].

The developed dataset contains the annual number of patents and publications for the four biobased technology groups presented as well as for non-biobased chemicals and pharmaceuticals as a reference for 15 nations from 1995-2019.[7] We account for the cumulative nature of knowledge while also considering knowledge depreciation, as implemented by similar studies [51]. For this purpose, we use a moving window approach that considers three years. Our data set primarily comprises the major industrialized countries, since less developed countries have very low patent and publication numbers and can thus not be considered in our econometric analysis.

3.2. Econometric strategy

In order to test the hypotheses developed in Section 2, we employ the following economic strategy using the data described above. We compute the revealed technological advantage (RTA) of countries in biobased technologies for both patent and publication data, which is a standard way of measuring specializations. The RTA in biobased technologies is the dependent variable used in all regressions. We estimate four linear models: Models (1) & (3) aim to explain the specialization for all biobased patents (1) and publications (3) within chemicals and pharmaceuticals. We therefore use the aggregated numbers of all biobased technologies in a panel setting with time and country fixed effects. In models (2) & (4), we analyse national specialization in specific biobased technologies. Accordingly, we extend the panel setting to country-year-technology observations, adding technology fixed effects to the model. For example, we can specify model (2) as follows:

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[4] There are other technology groups in chemicals and pharmaceuticals that can be assigned to the bioeconomy such as biobased adhesives, drop-in chemicals, or new technologies in biobased chemicals that cannot be clearly assigned to any other technology group [97]. These and others have also been reviewed. However, they either cannot be clearly distinguished from conventional technology groups in their classifications or the number of patents/publications is too low. Therefore, we decided to exclude these groups from the analysis. Accordingly, we do not claim that the database represents the entire bioeconomy or all bioeconomic activities in chemicals and pharmaceuticals.

[5] For all technology groups, IPC classes are related to chemicals and pharmaceuticals in order to focus on those sectors. This ensures that the scope of the individual technologies is similar to each other and to the comparison group of developing new technologies in chemicals and pharmaceuticals. The benchmark of all technologies in chemicals and pharmaceuticals is also delineated using IPC codes and Scopus classifications [62].

[6] The terms used in the IPC classification C12N are also the basis for the keywords used to filter the publication data: "detergent compositions; use of individual substances as detergents; soap or soap manufacture; resin soaps; recovery of glycerol" [77].

[7] Patent data originates from FIZ Karlsruhe and its STN platform, in collaboration with the Fraunhofer ISI. The publication data comes from Scopus, which is best suited for the selected research design [62].

$$Pat\_RTA_{cjt} = \beta_0 + \beta_1 Pat\_RTA_{cjt-1} + \beta_2\, ITC\_Pat_{ct} + \beta_3\, EPSI_{ct-1} + \gamma^k Controls^k_{ct} + \delta_c + \theta_j + \tau_t + \varepsilon_{cjt}$$

where c denotes the country, j technology and t time, Pat_RTA_{cjt-1}, ITC_Pat_{ct} and $EPSI_{ct-1}$ are the main independent variables, δ_c is a country fixed effect, θ_j is a technology fixed effect, τ_t is a time fixed effect, ε_{cjt} is the error term and k indicates the kth control variable. In addition to these regression models, appendix A lists models (5) to (12). These serve to test the robustness of the main models (1) to (4), using subsets for the respective technology groups.

The dependent variables are based on an aggregated count of all biobased technologies in the chemical and pharmaceutical sector for models (1) $RTA\_Pat\_BOE_{ct}$ and (3) $RTA\_Pub\_BOE_{ct}$, while we use a disaggregated dataset with the four technology groups in models (2) RTA_Pat_{cjt} and (4) RTA_Pub_{cjt}. The subsequent paragraphs provide an explanation of the operationalization of all variables, referring to patent data. We construct the variables for publication data in the same way. We calculate the RTA to measure specialization, following related studies [12,24]. The RTA captures the comparative advantage of a country c in a technology j at a time t, relative to the sum of patents of all technologies j in country c at time t, and relative to this relation on the global level. We apply a hyperbolic tangent transformation to normalize the RTA variable, restricting its values to a range of −100 to 100 [58].

$$RTA_{cjt} = tanh\left[ln\left(\frac{Patents_{cjt}\Big/\sum_j Patents_{cjt}}{\sum_c Patents_{cjt}\Big/\sum_{cj} Patents_{cjt}}\right)\right]$$

When computing the RTA, we do not use all patents as a reference group, but only patents in chemicals and pharmaceuticals (both biobased and not biobased), as we are interested in the relative importance of the bioeconomy in these sectors and not in the relative importance of biobased technologies to all technologies. This approach contrasts with methods used in other studies, such as measuring the proportion of (biobased) technologies in a country, or considering all technologies as a benchmark without sector-specific distinctions. Our method offers a different perspective by focusing on the sector-specific importance of biobased technologies. In this way, we also control for different national concentrations of the chemical and pharmaceutical sectors.

The RTA is also included within the independent variables to cover specialization in the previous year (Pat_RTA_{cjt-1} and Pub_RTA_{cjt-1}), capturing path dependencies. This allows to analyse to what extent the relative advantage of a country c, at time t-1, in a technology j has an impact on subsequent specializations.

The complexity of technology and knowledge receives much attention in the innovation literature [24,78]. The influence of technological complexity has been analyzed in previous studies on sustainable technology developments using the index of technological complexity (ITC), which we also use as one of our main independent variables [12,52,57]. To determine the ITC of biobased technologies (ITC_Pat_{ct} and ITC_Pub_{ct}), we use the method of reflections as proposed by [78] and used by [79].

The third main independent variable of interest is the Environmental Policy Stringency Index ($EPSI_{ct-1}$), which is a standard indicator for measuring the overall stringency of environmental policies at the national level. The EPSI is developed and published by the OECD, a detailed description is provided by [80]. In short, the EPSI is an index to measure the stringency of environmental policies implemented by countries. It assesses the degree to which environmental policies and regulations address environmental challenges and promote sustainability. The index combines various policy-related variables, such as regulatory standards, fiscal incentives, and enforcement measures, to provide a comprehensive measure of the stringency of environmental policies. By evaluating the comprehensiveness and effectiveness of a country's environmental policy framework, the EPSI helps to compare and benchmark the relative stringency of environmental policies across countries and track changes over time. Countries with high EPSI scores are often recognized as leaders in environmental policy and governance, demonstrating a strong commitment to environmental protection and sustainability.

Apart from the main variables presented, the following control variables capture further structural features that are likely to influence the national specialization in biobased technologies. We include the Herfindahl-Hirschman Index (HHI), to control for the concentration of different technologies j in country c in t-1 [12,57]. The HHI is calculated based on the number of patents per biobased technology group at the national level. The index is derived by summing the squared proportions of patents held by each biobased technology group j within a country c:

$$HHI_{ct-1} = \sum_{j=1}^{n_j}\left(100 * \left(\frac{Patents_{cjt}}{\sum_j Patents_{ct}}\right)\right)^2$$

This variable is used as a measure of concentration within the biobased technology portfolio, indicating the extent to which patenting activity is concentrated among specific technology groups. A higher HHI value suggests a higher concentration of patents within a few biobased technology groups, while a lower HHI value indicates a more balanced distribution of patents across multiple biobased technology groups. In addition, we control for regulatory quality (Reg_Q_{ct-1}) at the national level, which according to [81] measures the extent to which government regulations are transparent, efficient, and conducive to economic and social development. Regulatory quality reflects the ability of the government to formulate and implement effective regulations that promote fair competition, protect property rights, and ensure the overall stability and predictability of the business environment. Higher scores on the regulatory quality indicator indicate that a country has a well-functioning regulatory framework that supports economic growth, investment, and innovation.

For example, fuzzy regulation of patenting and property rights in the case of novel biotechnologies evokes great uncertainty for innovators, which might hinder innovation the bioeconomy [35,61]. We also control for available innovation capabilities and human capital at the country level, using the share of the population which at least finished secondary education at age 25 and older (edu_{ct-1}), which is a standard approach in the relevant literature [82]. Moreover, we control for gross domestic product (GDP) per capita and population density, i.e. GDP_Capita_{ct-1} and $Density_{ct-1}$.

We provide descriptions and descriptive statistics for all variables in Table 2. For the econometric estimations, the values of the independent variables are lagged by one year, except for ITC_Pat_{ct} and ITC_Pub_{ct}.[8] In addition, the independent variables are transformed in terms of optimal linearity to the dependent variable. We computed variance inflation factors (VIF) to check for problems with multicollinearity.

4. Results

For the empirical analysis, we first describe the specialization patterns of each country and then go into more detail, presenting the regression results. In the graphs shown below (Heat map Figs. 1–5), an RTA of 100 implies full specialization and −100 the least possible specialization in different technologies. In each figure, the arrangement of countries is based on their level of specialization in biobased patents in 2019.

When considering specializations within the bioeconomy in the chemicals and pharmaceuticals sectors, Japan, South Korea, and Germany appear to be trailing behind, focusing more on conventional (non-biobased) technologies within these sectors. Conversely, Australia, Canada, Denmark, the United Kingdom, and the United States exhibit a

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[8] We do not use time lags for ITC_Pat_{ct} *and* ITC_Pub_{ct} because these variables capture technological complexity of those patents and publications used to compute the dependent variable.

Table 2
Description of variables and descriptive statistics.

Variable	Description	N	Mean	SD	Min	Max
$RTA\_Pat\_BOE_{ct}$[a]	Revealed technological advantage based on the aggregated patent count of the four biobased technology groups in chemicals and pharmaceuticals	330	4.62	30.35	−68.80	74.85
$RTA\_Pub\_BOE_{ct}$[a]	Revealed technological advantage based on the aggregated publication count of the four biobased technology groups in chemicals and pharmaceuticals	330	10.32	25.99	−77.40	65.83
RTA_Pat_{cjt}	Revealed technological advantage for each biobased technology group in chemicals and pharmaceuticals based on patents	1320	0.16	39.84	−92.48	92.59
RTA_Pub_{cjt}	Revealed technological advantage for each biobased technology group in chemicals and pharmaceuticals based on publications	1320	2.98	36.73	−98.39	93.16
ITC_Pat_{ct}	Index of technological complexity of the four biobased technology groups based on patents (log)	1320	2.61	2.90	−2.30	4.61
ITC_Pub_{ct}	Index of technological complexity of the four biobased technology groups based on publications (log)	1320	2.61	2.89	−2.30	4.61
Pat_RTA_{cjt-1}	Specialization in patents in the previous year (RTA_Pat_{cjt} one year earlier)	1320	0.06	40.00	−96.69	92.59
Pub_RTA_{cjt-1}	Specialization in publications in the previous year (RTA_Pub_{cjt} one year earlier)	1320	2.56	36.65	−98.39	92.48
$EPSI_{ct-1}$	Environmental Policy Stringency Index in the previous year (log)	1320	0.66	0.72	−1.79	1.52
edu_{ct-1}	Share of the population having completed at least secondary education (% of age group 25 and older) in the previous year	1320	0.83	0.16	0.3	1
GDP_Capita_{ct-1}	GDP per capita (current US$) in the previous year	1320	35,509.46	18,289.28	781.74	91,254.04
$Density_{ct-1}$	Area (km^2)/population in the previous year	1320	168.07	143.18	2.39	513.95
Pat_HHI_{ct-1}	Herfindahl-Hirschman Index by patents in the previous year (sqrt)	1320	0.13	0.22	0	1
Pub_HHI_{ct-1}	Herfindahl-Hirschman Index by publications in the previous year (sqrt)	1320	0.18	0.20	0	1
Reg_Q_{ct-1}	Index on the quality of political regulation in the previous year	1320	1.25	0.63	−0.58	2.05

Number of countries: 15
Number of Technology groups: 4
Coverage: 1997–2019

[a] These two variables are the dependent variables in models (1) and (3) and therefore only cover 330 observations. All other variables refer not only to time *t* and country *c* but also to technology group *j* and contain significantly more observations (1,320).

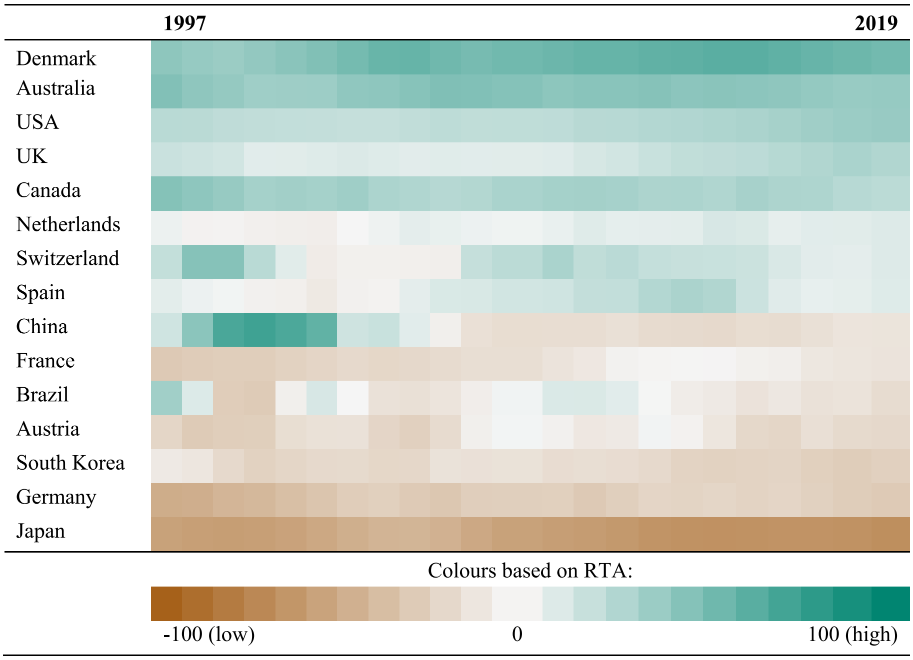

Fig. 1. Specialization in patents: RTA of biobased technologies in chemicals and pharmaceuticals (all biobased technologies).

comparative advantage in biobased technology groups within these sectors from 1997 to 2019 (Fig. 1). Notably, apart from China, there is a lack of clear shifts in these patterns among countries. This suggests that, on an aggregate level across the four technology groups, promoting the bioeconomy proves challenging for countries that did not possess early specialization in biobased technologies.

Examining the evolution of each biobased technology group provides a more nuanced perspective, revealing contrasting trajectories where some countries have developed a comparative advantage over time while others have lost it (see Figs. 2–5). However, when it comes to patents in biotechnology, biopharmaceuticals, and biobased detergents, diversification without prior specialization seems highly challenging. In contrast, six countries have successfully diversified into bioplastics, establishing a comparative advantage over time. One possible explanation for this divergence is that the production of bioplastics requires relatively fewer resources, including financial investment, compared to other technology groups like biotechnology. Additionally, the wide range of application areas for bioplastics contributes to their higher diversification potential. On the other hand, the biotechnology industry, while offering greater diversity in applications, has experienced slower growth and is dominated by global companies. This dominance creates significant entry barriers for non-specialized countries.

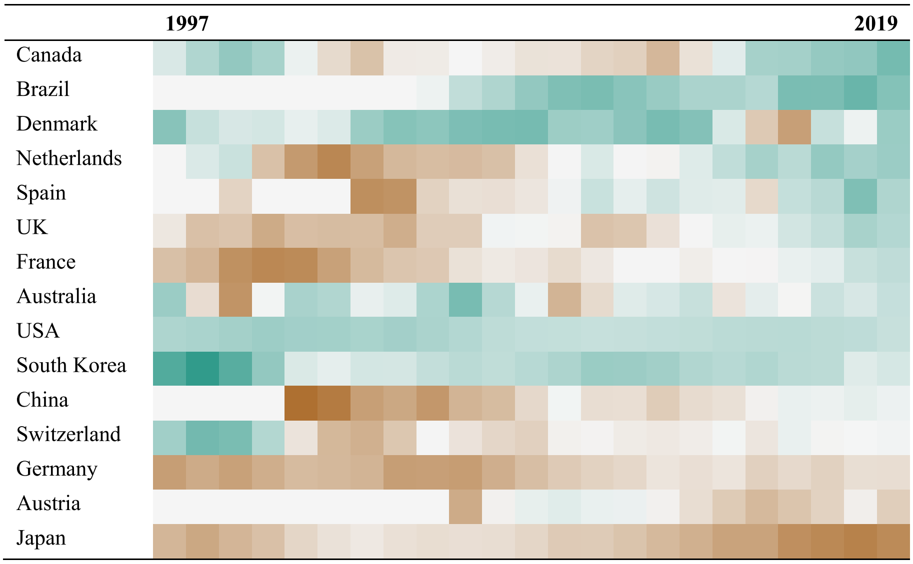

Fig. 2. Specialization in patents: RTA of bioplastics in chemicals and pharmaceuticals.

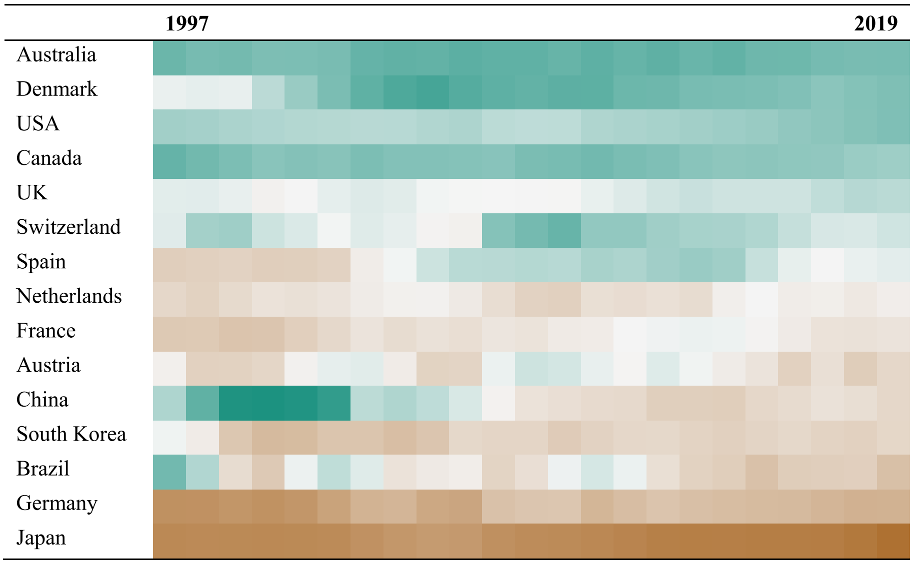

Fig. 3. Specialization in patents: RTA of biopharmaceuticals in chemicals and pharmaceuticals.

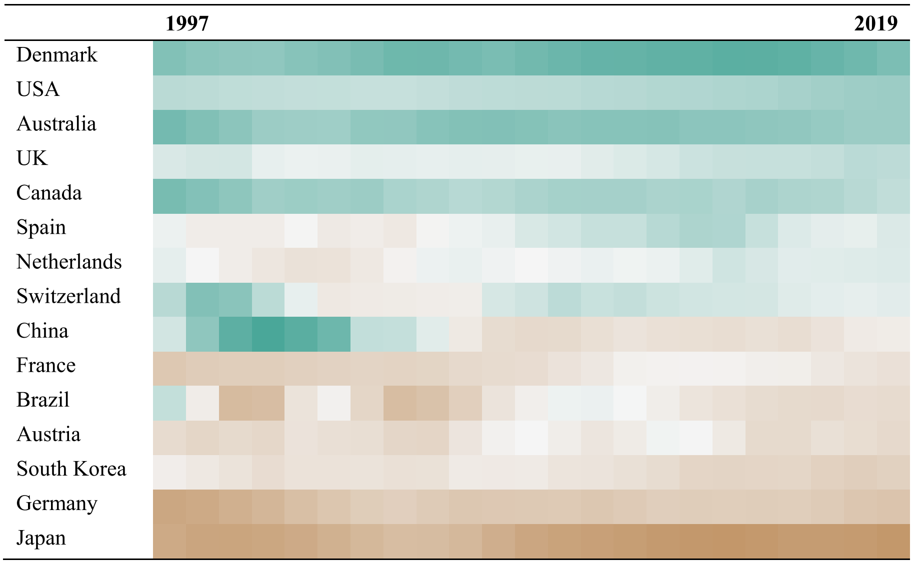

Fig. 4. Specialization in patents: RTA of biotechnology in chemicals and pharmaceuticals.

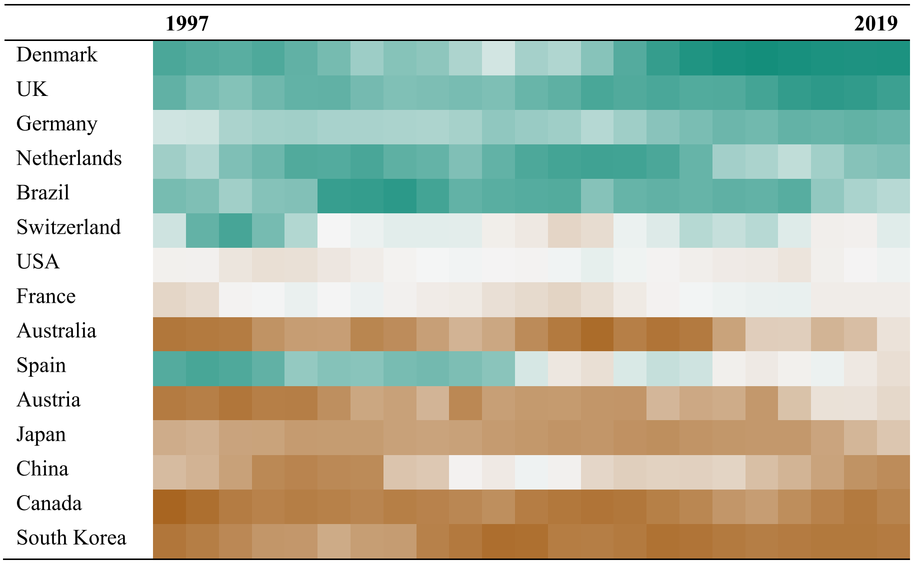

Fig. 5. Specialization in patents: RTA of biobased detergents in chemicals and pharmaceuticals.

These findings align with observations on technology maturity from other studies. In this context, countries are less likely to diversify into more mature technologies [12,48,57,83]. There may be other technology groups that share similarities with bioplastics but were not included in the analysis due to a limited number of cases.

These technology groups may also cater to smaller niches, offering diverse applications across various sectors of the economy, such as biobased adhesives. Consequently, the patterns observed for bioplastics could potentially provide insights into the development of numerous other niche technologies within the bioeconomy. This stands in contrast to the more established fields of biopharmaceuticals and biotechnology, which have already undergone significant development and advancement.

The findings from the publication data were analyzed using the same methodology as the patent data and are presented in Appendix A, Fig. 6–10. The calculations reveal variations in the degree of specialization between patents and publications across countries. Countries that exhibit specialization in specific technologies through patents often show less specialization in publications, and vice versa. In the case of bioplastics, the trends and interpretations observed in patents can also be observed in basic research when examining the publication data (Fig. 7). It is noteworthy that in the case of biopharmaceuticals, there are countries that exhibit comparably low specialization in both patents and publications (Fig. 3 and Fig. 8).

The divergent specialization patterns observed between countries in terms of patents and publications raise the question of why basic research (publications) and applied research (patents) exhibit contrasting trajectories in the development of new biobased technologies within the chemicals and pharmaceuticals sectors. Countries frequently display opposite specializations in patents and publications, with rare instances of similar specialization patterns. One possible explanation for this observation, as suggested by [84] is that the emergence of innovations does not follow a linear path but relies on interconnected processes and feedback loops across different stages of the innovation process. Additionally, in the context of chemicals and pharmaceuticals, the dominant innovation mode is often the STI mode [36]. Consequently, innovation capabilities are distributed globally, making it unlikely for a national innovation system to emerge that encompasses both applied and basic research in the same biobased technology domain [85].

Analytical knowledge serves as a fundamental source for innovation development in the economic sectors and research fields under consideration in this study [86]. Such knowledge is extensively available through publications and can form the basis for applied research in other countries, provided that the necessary competencies are in place [87]. Consequently, the scientific competence that emerges in one country, along with its analytical capabilities, can be advantageous for other countries to leverage. As a result, positive effects of basic research on specialization in applied research within the biobased chemicals and pharmaceuticals domain are not restricted solely to the country of publication. Theoretically, depending on the presence of human capital, these benefits can be harnessed by all countries.

The regression results presented in Table 3 demonstrate that the patterns underlying specialization processes in biobased patents and biobased publications are quite similar.[9][10] There is no problem with multicollinearity in our models, as all models have mean VIF values below 2. The results partially support hypothesis $\mathbf{H_1}$, as high technological complexity of biobased technologies tends to hinder national specializations in publications on biobased technologies (model 4). For the specialization in biobased patents (model 2), ITC_Pat_{ct} also shows a negative but not significant effect. Therefore, the (negative) effect of complexity of biobased technologies for national specializations is more relevant for scientific performance of countries than for patent applications. These findings further support the significance of scientific research for the bioeconomy and underscore its inherent complexity. Similar tendencies have been observed in studies examining sustainable technologies, corroborating the relevance of these results [12]. This finding aligns with the research conducted by [88] which highlights the challenges of specializing in complex technologies. Consequently, nations may adopt strategies that avoid pursuing highly complex technologies to mitigate what has been referred to as a “diversification dilemma” [88]. Additionally, these findings reinforce the earlier results on diversification, as evidenced by the heatmaps, which indicated the limited capacity of countries to diversify into new biobased technologies. Taking into account the bioeconomy innovation types discussed by [29] introduces another dimension to explain the variation in complexity and the likelihood of diversification among different biobased technologies. The substitution nature of bioplastics, replacing previously used resources, differs from biotechnology, which establishes

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[9] In addition, a correlation table with all variables is provided in Appendix A (Table 4).

[10] As can be seen in Table 5 (Appendix A), the robustness test of these results in models (5) to (12) support these results and trends, also for the explanation of specializations by technology group in patents and publications.

Table 3
Regression results on specialization of biobased technologies in chemicals and pharmaceuticals.

	Patents		Publications	
	RTA Bioeconomy (1)	RTA biobased technologies (2)	RTA Bioeconomy (3)	RTA biobased technologies (4)
ITC_Pat_{ct}		−0.022 (0.124)		
ITC_Pub_{ct}				−0.385*** (0.149)
Pat_RTA_{cjt-1}	0.816*** (0.032)	0.806*** (0.017)		
Pub_RTA_{cjt-1}			0.773*** (0.038)	0.770*** (0.017)
$EPSI_{ct-1}$	−1.773 (1.313)	0.503 (1.067)	−0.769 (1.004)	−0.851 (1.253)
edu_{ct-1}	−0.279 (8.787)	−1.338 (7.576)	−4.793 (6.279)	−11.252 (7.808)
GDP_Capita_{ct-1}	0.0001 (0.0001)	0.00005 (0.0001)	−0.0002*** (0.0001)	−0.0002*** (0.0001)
$Density_{ct-1}$	0.079 (0.076)	0.094 (0.066)	−0.028 (0.057)	−0.080 (0.069)
Pat_HHI_{ct-1}	−24.360 (17.459)	−34.430** (15.205)		
Pub_HHI_{ct-1}			6.797 (4.732)	16.986*** (5.028)
Reg_Q_{ct-1}	−1.879 (2.556)	−1.120 (2.218)	−3.389* (1.854)	−5.068** (2.271)
Time Fixed Effects	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes	Yes
Tech Fixed Effects	No	Yes	No	Yes
Observations	330	1320	330	1320
Mean VIF	1.25	1.16	1.5	1.19
Adjusted R2	0.714	0.627	0.773	0.674
F Statistic	123.381*** (df = 7; 287)	287.816*** (df = 8; 1231)	166.002*** (df = 7; 287)	351.751*** (df = 8; 1231)

Note: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

novel processes enabling entirely new products and behaviors. As a result, countries tend to prioritize diversification towards incremental biobased substitutions rather than radical bioeconomy innovations, which inherently involve greater complexity. However, the data do not cover all innovative developments that emerge from the technology groups included, as they are sometimes applied in other sectors.

The coefficients of Pat_RTA_{cjt-1} & Pub_RTA_{cjt-1} show that when a country specializes in a biobased technology, it usually leads to a comparative advantage in this technology in the following year. Conversely, it is difficult for countries to gain a new comparative advantage in biobased technologies, both in terms of patents and publications, if they are not yet specialized, which lends strong support for hypothesis $\mathbf{H_2}$. As such, our results point to strong path dependencies in technological specializations.

Regarding the effect of environmental policies, we do not find support for our hypothesis that stringent environmental policies increase the level of specialization in biobased technologies (hypothesis $\mathbf{H_3}$). In fact, we find that $EPSI_{ct-1}$ even shows a negative but not significant effect for models (1), (3) and (4). Consequently, the analysis does not uncover a significant association between stringent environmental policies and specialization in both biobased patents and publications. However, all these findings should be interpreted with caution, as the policies considered in $EPSI_{ct-1}$ primarily target the reduction of greenhouse gas emissions. It is important to note that the selected biobased technologies only have a limited contribution to the reduction of greenhouse gas emissions and, as a result, the observed lack of a significant relationship between stringent environmental policies and specialization in biobased technologies does not mean that policy and regulation are not important to drive the bioeconomy.

The control variables are partially significant and show only limited support for the assumed effects. A higher share of the population with secondary education (edu_{ct-1}) seems to inhibit specialization in biobased patents and publications (not significant). Increasing GDP (GDP_Capita_{ct-1}) and population density $(Density_{ct-1})$ seem to lead to higher levels of specialization in biobased patents but to lower levels of specialization in biobased publications. The positive effects of Pub_HHI_{ct-1} show that high concentration in one of the four technology groups favors specialization opportunities in publications. For patents, we find the opposite, as indicated by negative effects of Pat_HHI_{ct-1}. However, both effects only become significant when technology fixed effects are taken into account in models (2) and (4). When countries focus on one of the technology groups in the bioeconomy in basic research, they are also more likely to develop specializations. Based on these observations, it can be inferred that the development of biobased technologies in basic research in the chemicals and pharmaceuticals sectors exhibits a higher degree of path dependency once countries have embarked on these technological trajectories [89]. The results for Reg_Q_{ct-1} indicate that regulatory quality has a negative and statistically significant effect on the specialization in biobased publications. This suggests that countries with higher regulatory quality are less likely to specialize in biobased publications. The effect of regulatory quality is also negative but not significant for the patent models. This may imply that regulatory quality primarily influences the development and dissemination of knowledge through publications in the bioeconomy, while its impact on other dimensions of biobased technology specialization remains less pronounced.

The econometric models employed in this study exhibit certain limitations and challenges that warrant further investigation. Specifically, when exploring the relationship between new biobased technologies and political regulation, the inclusion of environmental policy indicators was a pragmatic choice. However, these indicators may not fully capture the nuanced measurements specific to bioeconomy policy. Consequently, there is a need to develop a comprehensive indicator for bioeconomy policy that encompasses the diverse strategies adopted by different countries and the European Union. Such an indicator would provide a more accurate and comprehensive understanding of the role of bioeconomy policies in shaping the national specialization in biobased technologies. Future research should strive to establish and refine this indicator to enhance our understanding of the complex interplay between bioeconomy policies and technological developments [10,11,90]. We acknowledge that our approach cannot effectively portray the development of new sectors or the evolution and disappearance of existing ones as a result of transformative processes, especially in cases where bioeconomic innovations have multidimensional impacts on different industries. Recognizing the inherent complexity of such interactions, we endorse the need for a nuanced discussion on innovation dynamics in the bioeconomy beyond linkages to specific sectors. For instance, some bioeconomy innovations hold the potential to revolutionize multiple sectors simultaneously, rather than being confined to a single domain. These innovations have the capacity to forge entirely new value chains and to create novel industries. Regrettably, the scope of our current data does not extend to fully capturing these transformative dynamics. However, we strongly urge fellow researchers to delve into exploring these disruptive potentials inherent in some bioeconomy innovations [9,34]. By incorporating more specific measurements and also including small and less developed countries in the analyses, a deeper understanding of the effects and their implications could be achieved. Such an inclusive analysis would provide a more robust foundation for formulating targeted policies and interventions that address the specific challenges and opportunities faced by many countries in the context of sustainable development and bioeconomy transitions. However, due to the very small number of patents and publications, we were not able to include more countries in our analysis.

Another limitation of this study is that we are unable to fully assess the extent to which different biobased technologies actually contribute to more sustainable futures.

5. Conclusion

In this paper, we conducted an empirical analysis using patent and publication data to examine the specialization and diversification patterns of countries in the chemical and pharmaceutical sectors regarding biobased technologies. Our study aimed to expand existing research on sustainable technologies by investigating the specific case of biobased technologies. The findings of our study reveal strong path dependencies in the specialization of biobased technologies, as countries' degree of specialization in previous years significantly influences their current specialization. Moreover, the high technological complexity associated with biobased technologies poses challenges for countries in establishing new comparative advantages, particularly in the realm of basic research, as evidenced by publication data.

Additionally, our results indicate that stringent environmental policies and perceived regulatory shortcomings can act as barriers to national specialization in biobased technologies. These findings highlight the significance of policy frameworks and their implications for the development of biobased technologies. Furthermore, our study uncovers a divergence between the degree of specialization in basic research and applied research, indicating complex configurations within global bioeconomy innovation systems. These observations underscore the need for further research to gain a deeper understanding of these dynamics.

The identification of specific patterns in patents and publications offers a robust foundation for future research focused on the crucial sectors of chemicals and pharmaceuticals within the bioeconomy. Moreover, this study successfully differentiated between biobased and non-biobased technologies, specifically in the context of chemicals and pharmaceuticals. Expanding the analysis of technological development patterns to other sectors within the bioeconomy would help validate the generalizability of our findings and provide a more solid basis for policy making.

Furthermore, the specific characteristics of each technology group play a significant role, as evidenced by distinct patterns observed within the four similar technology groups analyzed. Diversification, for instance, appears to be challenging in most cases, with the exception of bioplastics, where several countries were able to achieve new specializations during the study period. This underscores the importance of delving deeper into technology specific attributes in future research, with the level of technological maturity probably being a significant factor of consideration.

The findings of this study align with the arguments presented in the existing literature on policies for sustainable technologies, thus reinforcing the following policy implications. It is evident that systemic adjustments are crucial for fostering the advancement of the bioeconomy. While there is already substantial EU funding allocated to bioeconomy activities, it is crucial to ensure that these funds are targeted to address the specific national contexts and technology-specific conditions. This targeted approach will enhance the effectiveness of the funding and its impact on promoting the growth of biobased technologies within the chemicals and pharmaceuticals sectors [14,27,29,35]. Our findings underscore crucial insights for shaping the future of biobased technologies in the chemical and pharmaceutical sectors. Policymakers are encouraged to design policies that build upon existing strengths in these sectors, mitigating challenges posed by the technological complexity and regulatory environments. Tailoring funding to align with the unique needs of different technology groups and fostering environments conducive to innovation is essential. For practitioners, the focus should be on leveraging diversification opportunities, particularly in emerging fields like bioplastics, and harnessing the unique attributes of various biobased technologies. Collaboration with academic institutions can bridge the divide between research and practical application, while transparent reporting and active participation in policy development can ensure a more cohesive approach towards advancing the bioeconomy. This concerted effort between policymakers and practitioners is vital for the future development of biobased technologies.

From a researcher's perspective, we would like to call for more effort in developing indicators for (innovation in) the bioeconomy [9,18]. There is little guidance or rules for companies and countries on how to report on progress in the bioeconomy. As a result, there is a lack of data that could form the basis for empirical studies. As such, the derivation of specific strategies for policy recommendation is cumbersome.

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CRediT authorship contribution statement

Lennart Fischer: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft. **Sebastian Losacker:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Sven Wydra:** Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

No potential competing interest was reported by the authors.

Data availability

The data that has been used is confidential.

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Appendix A

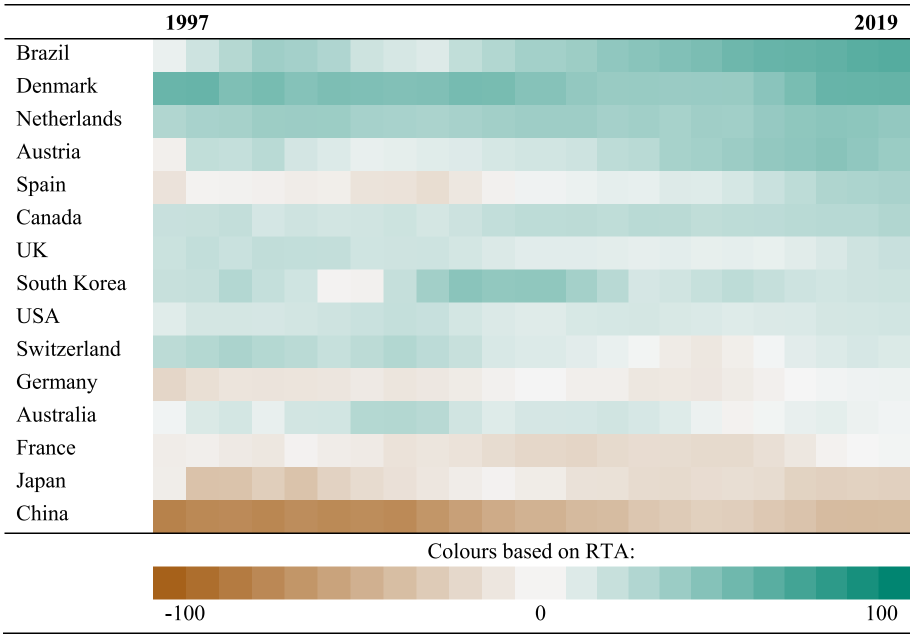

Fig. 6. Specialization in publications: RTA of biobased technologies in chemicals and pharmaceuticals (all biobased technologies).

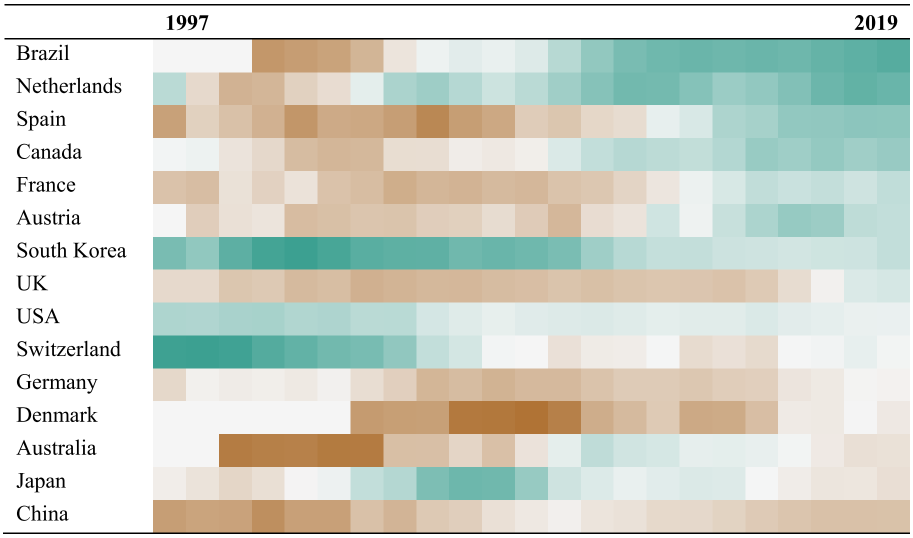

Fig. 7. Specialization in publications: RTA bioplastics in chemicals and pharmaceuticals.

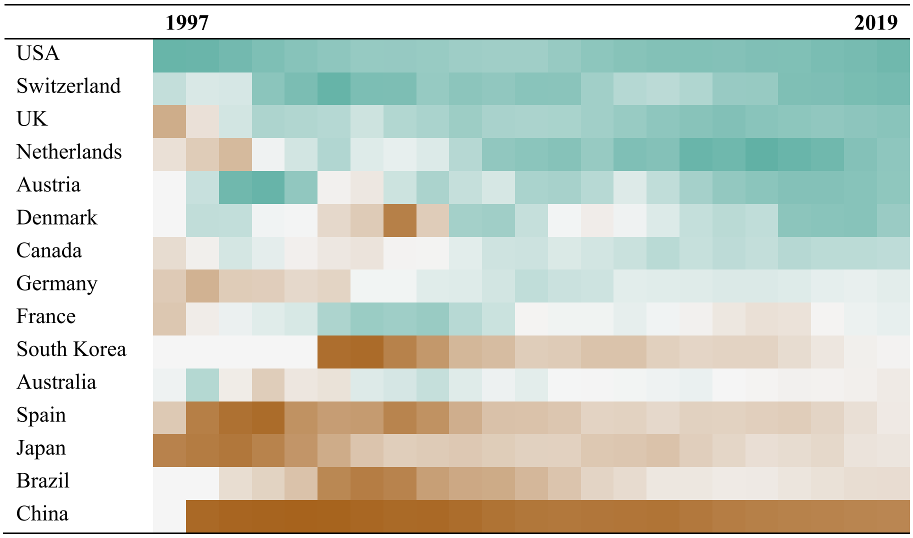

Fig. 8. Specialization in publications: RTA biopharmaceuticals in chemicals and pharmaceuticals.

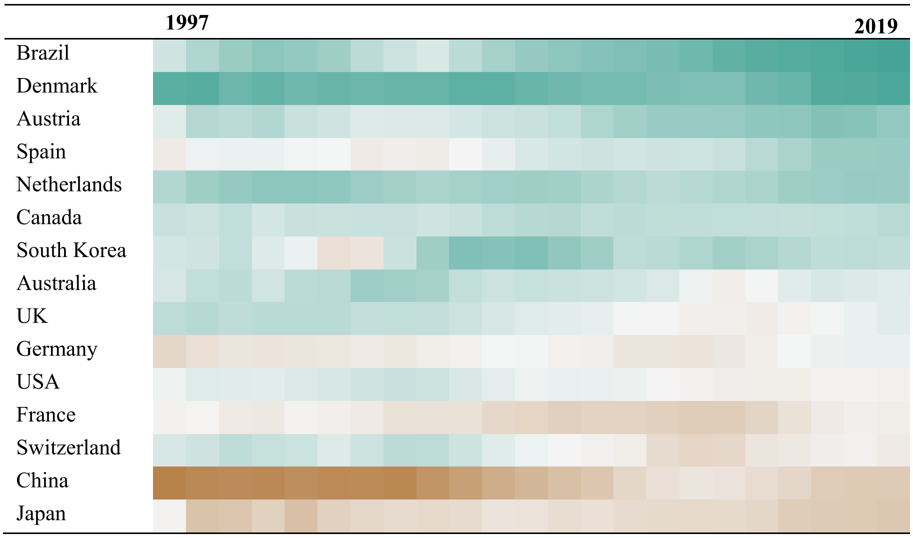

Fig. 9. Specialization in publications: RTA biotechnology in chemicals and pharmaceuticals.

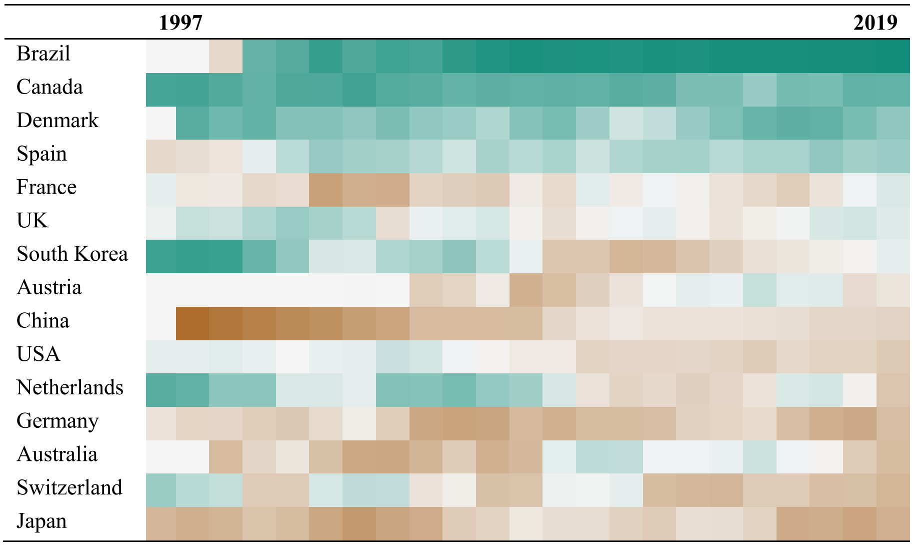

Fig. 10. Specialization in publications: RTA biobased detergents in chemicals and pharmaceuticals.

Table 4
Correlation Table

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
[1] Pat_RTA_{cjt-1}											
[2] ITC_Pat_{ct}	0.033										
[3] Pat_HHI_{ct-1}	0.035	0									
[4] Pub_RTA_{cjt-1}	0.247***	−0.06*	0.027								
[5] ITC_Pub_{ct}	−0.019	0.264***	0	0.024							
[6] Pub_HHI_{ct-1}	−0.031	−0.002	0.875***	−0.079**	−0.003						
[7] $EPSI_{ct-1}$	−0.079**	0.017	0.056*	0.068*	0.023	−0.06*					
[8] edu_{ct-1}	0.044	0.01	0.259***	0.18***	0.014	0.063*	0.668***				
[9] GDP_Capita_{ct-1}	0.136***	0.015	0.184***	0.192***	0.021	−0.105***	0.708***	0.71***			
[10] $Density_{ct-1}$	−0.242***	0.001	−0.144***	−0.019	0.001	−0.114***	0.308***	0.119***	0.028		
[11] Reg_Q_{ct-1}	0.163***	0.003	0.137***	0.254***	0.002	−0.132***	0.563***	0.739***	0.747***	0.039	

Note: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table 5
Robustness check bioeconomy RTA in chemistry and pharmaceuticals

	Patents				Publications			
	Bioplastics	Biopharmaceuticals	Biotechnology	Biobased detergents	Bioplastics	Biopharmaceuticals	Biotechnology	Biobased detergents
	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
$Pat\_RTA\_plastic_{RTA\,cjt-1}$	0.735***							
	(0.041)							
$Pat\_RTA\_pharma_{RTA\,cjt-1}$		0.803***						
		(0.032)						
$Pat\_RTA\_biotech_{RTA\,cjt-1}$			0.817***					
			(0.031)					
$Pat\_RTA\_detergent_{RTA\,cjt-1}$				0.835***				
				(0.036)				
$Pub\_RTA\_plastic_{RTA\,cjt-1}$					0.879***			
					(0.030)			
$Pub\_RTA\_pharma_{RTA\,cjt-1}$						0.641***		
						(0.037)		
$Pub\_RTA\_biotech_{RTA\,cjt-1}$							0.781***	
							(0.037)	
$Pub\_RTA\_detergent_{RTA\,cjt-1}$								0.640***
								(0.043)
$EPSI_{ct-1}$	6.869**	−1.986	−2.248*	−0.864	0.842	−3.923	−1.115	−0.306
	(3129)	(1792)	(1245)	(1986)	(2664)	(2654)	(1104)	(3030)
edu_{ct-1}	6.208	1.970	−1.013	−6.762	−30.890*	−17.708	−8.695	30.683
	(22,430)	(12,024)	(8257)	(14,025)	(16,841)	(16,255)	(6910)	(19,212)
GDP_Capita_{ct-1}	−0.0001	0.00004	0.0001	0.0001	0.0001	−0.0003*	−0.0003***	−0.0002
	(0,0002)	(0,0001)	(0,0001)	(0,0001)	(0,0001)	(0,0001)	(0,0001)	(0,0002)
$Density_{ct-1}$	0.254	0.188*	0.065	−0.124	−0.007	0.125	−0.049	−0.517***
	(0.195)	(0.105)	(0.071)	(0.122)	(0.146)	(0.140)	(0.062)	(0.186)
Pat_HHI_{ct-1}	−27.702	−46.124*	−10.767	−46.218				
	(44,795)	(24,059)	(16,498)	(28,778)				
Pub_HHI_{ct-1}					2.364	22.192**	14.665**	29.998**
					(10,707)	(10,185)	(5766)	(12,430)
Reg_Q_{ct-1}	−9.949	3.080	−4.776**	6.539	−13.063***	−7.106	−1.554	1.703
	(6537)	(3509)	(2424)	(4119)	(4886)	(4692)	(2005)	(5563)
Time Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	330	330	330	330	330	330	330	330
Mean VIF	1.19	1.26	1.25	1.23	1.25	1.19	1.61	1.31
Adjusted R2	0.488	0.708	0.731	0.670	0.769	0.487	0.815	0.560
F Statistic (df = 7; 287)	50.722***	119.741***	134.023***	101.570***	162.488***	50.559***	213.340***	65.891***

Note: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Appendix B

Using a similar definition of *bioplastics* [91] calculate a savings potential of 138 million tons of CO_2 equivalents per year. This could replace 65.5 % of conventional plastics. In addition, there is already a broad base of biodegradable, biobased plastics. However, they vary widely in their structure and properties. As a result, their suitability for different applications and products varies and they are not always more sustainable [64,70]. In the future, based on the chosen delimitation and the established research structures, there is great potential to produce bioplastics sustainably for many applications in the long term [55,56,91]. However, the consequences for ecosystems and sustainability must always be weighed in detail [64,65,70,72].

Biopharmaceuticals are seen as an essential factor to prevent negative effects of the healthcare market, such as additional pollution, and to be able to treat as many diseases as possible in the future [66,73,74]. At the same time, there is strong growth and a large number of approved products, with multinational companies dominating [63,73]. While biopharmaceuticals are seen as a sustainable solution for the healthcare sector, water consumption in production is comparatively high, with approaches to further reduce water consumption and thus save additional emissions [66,92].

Biotechnology is the most developed of the four technology groups and has already made a significant contribution to economic development [21]. So far, specific patent analyses have been carried out in particular on the basis of individual applications such as fungi [21,22]. The development of sustainable biotechnological solutions in chemicals and pharmaceuticals is exemplary because the processes that were previously replaced emitted many times more CO_2 [22].

For *biobased detergents*, there is a wide range of applications and the respective biobased detergent compositions vary in suitability depending on the purpose of the product and the efficiency in production [68,93]. Conventional detergents are often harmful to the environment, whereas biobased detergents are the solution approach to make the corresponding applications and products sustainable [93,94]. Nevertheless, even for biobased detergents, explicit environmental impacts should always be studied in the context of achieving the bioeconomy's goal of long-term sustainability [94].

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