

Article

Monitoring Bioeconomy Transitions with Economic–Environmental and Innovation Indicators: Addressing Data Gaps in the Short Term

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Abstract: Monitoring bioeconomy transitions and their effects can be considered a Herculean task, as they cannot be easily captured using current economic statistics. Distinctions are rarely made between bio-based and non-bio-based products when official data is collected. However, production along bioeconomy supply chains and its implications for sustainability require measurement and assessment to enable considered policymaking. We propose a starting point for monitoring bioeconomy transitions by suggesting an adapted framework, relevant sectors, and indicators that can be observed with existing information and data from many alternative sources, assuming that official data collection methods will not be modified soon. Economic–environmental indicators and innovation indicators are derived for the German surfactant industry based on the premise that combined economic–environmental indicators can show actual developments and trade-offs, while innovation indicators can reveal whether a bioeconomy transition is likely in a sector. Methodological challenges are discussed and low-cost; high-benefit options for further data collection are recommended.

Keywords: Bioeconomy monitoring; transition framework; surfactant industry; bio-based share; fossil resource substitution; diffusion of innovations

Highlights

- Findings indicate growth in innovative, bio-based products and possibly a beginning transition from a fossil-based economy to a bio-based economy.
- Despite considerable innovation potential, stagnating patent indicators reflect declining market optimism.
- Limitations in data for monitoring the bioeconomy can be overcome in the short-term by integrating diverse data sources.
- A modified Driver-Pressure-State-Impact-Response framework is proving beneficial for the analysis of high-resolution sectors and indicators for an initial monitoring of the bioeconomy.
- Fossil-resource saving may be in the order of 29 MJ per € of production costs.

1. Introduction

Monitoring the bioeconomy is becoming increasingly important, as the demand for products based on biogenic resources, including biomass from agriculture, forestry, fishery, and organic waste, is increasing and new bio-based technologies (e.g., gene editing) are being explored in various sectors. There is, consequently, a growing interest among governments in setting up bioeconomy monitoring systems that can enable the measurement and assessment of bioeconomy supply chains—from biomass extraction to consumption and recycling—and their implications for sustainability in order to facilitate considered policymaking [1,2]. Quantification of bioeconomies, as for example in [3,4], enables comparative analyses of bioeconomies' performances and promote sustainable transitions. Measuring bioeconomy sectors has the advantage that biomass input can be channeled to those sectors that use it most efficiently and effectively in terms of sustainability.

However, monitoring bioeconomies and their economic, environmental, and social effects can be seen as a Herculean task. Each bioeconomy can be considered a cross-sectoral economy (i.e., an economy spanning various sectors), similar to the environmental economy or health care industry. A key problem for bioeconomy monitoring is that when data is collected by governments for official economic statistics, distinctions are rarely made between bio-based and non-bio-based products. Consequently, bioeconomy contributions are not clearly delineated in official statistics, making their complete depiction difficult and presumably costly.

One result of this lack of sufficient and reliable data is that those responsible for implementing coherent and continuous monitoring are faced with many different and often conflicting statements concerning the bioeconomy, because varying sectoral demarcations are assumed. Sectors included in various studies and the monitoring systems employed by countries differ widely because they—especially the latter—are oriented towards differing objectives [5–8]. The European Commission describes the bioeconomy in terms of three sectors, called “core,” “partial,” and “indirect” bioeconomy [1]. Meanwhile, the German Ministry of Education and Research (BMBF) and the German Ministry of Food and Agriculture (BMEL) distinguish ten economic sectors that are relevant for the bioeconomy but do not fully belong to it [9], whereas the German Bioeconomy Council includes all value chains—from the production of biomass in the agricultural and forestry sectors, fisheries and aquaculture, culture media (microbial production), and waste management, to the end products derived from them [10].

While the primary sectors of agriculture and forestry are always included and the chemical sector, for example, is at least partly considered in most monitoring systems internationally [6], methods and results generally differ (see Table 1). Following the definition of the German Bioeconomy Council, for example, [11] consider all sectors that have some biomass input as part of the German bioeconomy. In their study, the agricultural biomass input share of each 4-digit level sector, according to the NACE Rev. 2 code, is estimated in terms of value, based on a regular survey called “Materials and Goods Received.” NACE is the acronym used to designate the statistical classification of economic activities in the European Community. It is a framework for collecting and presenting statistical data. From the survey, however, it is not discernible whether biomass input is actually used in the production process or if some input of processed goods is bio-based but not declared as such. Another approach has been to estimate bio-based shares at the product level (8-digit according to the Combined Nomenclature, a tool for classifying goods: https://ec.europa.eu/taxation_customs/business/calculation-customs-duties/what-is-common-customs-tariff/combined-nomenclature_en) with the support of experts [12]. This kind of data has been used for the calculation of socioeconomic indicators for the EU's bioeconomy [3,4] and in an input–output model of the Polish bioeconomy [13]. Meanwhile, [14] do not include bio-based chemicals in their estimation of Japan's bioeconomic GDP. In short, the sectors that belong to the bioeconomy and the determination of the bio-based shares of partially bio-based sectors are still under discussion.

Furthermore, either economic or environmental performance is measured, but not both [15]. Already, existing monitoring systems emphasize economic targets [5], and, thus, a number of studies

rely on the results from economic indicators—above all, employment and value added [3,11,13,14]. Others, however, focus on environmental sustainability [16–18]. This divide indicates that a holistic framework and appropriate indicators that can display trade-offs between two or more objectives are missing.

Table 1. Overview of bioeconomy sectors and indicators suggested in this study compared with current literature.

Literature	Bioeconomy Sectors Covered	Economic Indicators	Environmental Indicators	Innovation Indicators
This study	Bio-based manufacturing sectors with substitution potential (case here: bio-based surfactants. More sectors in [19].	Number of employees, gross value added, turnover, foreign sales, investment	Energy consumption, land footprint, fossil-resource saving	Publications, patents
Biber-Freudenberger et al. 2018 [17]	Primary and high-tech bioeconomy sectors	Value added, employment, exports	Selected indicators linked to SDGs	Patent applications
Capasso and Klitkou 2020 [20]	Sectors with a bio-based share	Value added, employment, productivity	-	-
D’Adamo et al. 2020 [4]	Sectors with a bio-based share	Employment, turnover, value added	-	-
Efken et al. 2016 [11]	Sectors with bio-based inputs	Employment, gross value added	-	-
Egenolf and Bringezu 2019 [18]	Not specified		Agricultural land, forest, water, material, climate footprints	
Frietsch et al. 2016 [21]	Sectors with bio-based related patents			patents
Fuentes-Saguar et al. 2017 [22]	Selected bioeconomy sectors	Output and employment multipliers		
Iost et al. 2019 [23]	Sectors with bio-based inputs	Employment, gross value added, turnover	-	-
Jander and Grundmann 2019 [24]	Bio-based substitute products	Substitution share, fossil-resource saving	-	-
Loizou et al. 2019 [13]	Sectors with a bio-based share	Output, employment, income multipliers	-	-
Ronzon and M’Barek 2018 [3]	Sectors with a bio-based share	Number of persons employed, turnover, value added, labor productivity, location quotient	-	-
Wen et al. 2019 [14]	Selection of mainly bio-based sectors + bioenergy	Value added	-	-
Wydra 2020 [25]	Sectors with a bio-based share			R&D expenditures, patents

Given the limited financial resources for upcoming bioeconomy monitoring needs, no agreement has been reached so far among scholars on what priority areas should be for monitoring in the short term, or appropriate overall boundaries for the long term. Taking a practical approach, we recommend

aiming first at monitoring the most important sectors and indicators in depth and, then, gradually including them in a larger monitoring framework. In the present article, we propose a feasible starting point for such bioeconomy monitoring efforts based on two kinds of indicators. First, economic–environmental indicators can reveal actual transition developments and trade-offs, while, second, innovation indicators show where further contributions to bioeconomy transition may be expected. Innovations have been found to be core to a bioeconomy transition [26]. By proposing these as core indicators, we seek to contribute towards the ongoing debate regarding what should be measured during bioeconomy transitions. To tackle the problem of separating out the bioeconomic components of an industry and showing how they can be unambiguously described, we focus here on a case from manufacturing—the German surfactant industry—chosen for this study as a priority area for monitoring.

Below, we provide details on calculating our selected indicators, combining existing data and information in novel ways. Our analysis is based on economic classifications and relevant indicators that can be observed with information and data from many alternative sources, based on the assumption that current classification schemes and official modes of data collection will not be appropriately modified in the near future. Because of the scale of this challenge, we have set our main focus for now on a few selected indicators and sectors, but it is clear that this initially limited scope needs to be extended by including more indicators and sectors in the medium and long term. In the conclusion, we discuss methodological limitations and data gaps and provide hands-on options for improving the suggested indicators that can hopefully close the most important gaps with relatively few additional resources.

2. Analytical Framework

The currently existing definitions of the term bioeconomy are not completely congruent and offer scope for interpretation. Against this background, we adopt a broad definition for building an objective, comprehensive, and value-neutral bioeconomy monitoring system. This means including all value chains that use biological resources. Both already quantitatively relevant industrial sectors, such as the timber industry or the food and beverage sector, should be taken into account, as well as emerging sectors that have not yet reached significant production volumes but hold high innovation potential, such as bio-based polymers and plastics. All biological resources need to be considered, including all types of biomass: vegetable, animal, and waste streams, as well as processes in which biological resources, such as living organisms (plants, animals, microorganisms) or parts thereof (e.g., DNA, enzymes, etc.), are used in the production process.

This study is further guided by an extended version of the Bioeconomy Transition Framework (BTF) described in [24]. When investigating bioeconomy transitions, such a framework becomes indispensable to achieve a common understanding between the indicator developers and users on broad and dynamic constructs with numerous objectives, drivers, constraints, and possible responses. The BTF is developed further here (Figure 1) in order to include not only the transition from fossil-based to bio-based economies, but also other kinds of “transformation paths” [27], such as towards greater food security, or “visions,” such as more ecologically sound ways of producing goods [28]. “Drivers” are now taken to include all bioeconomy sectors following the above definition, and not only bio-based substitute goods (i.e., biomaterials and bioenergy) as in the original framework. However, with our case study, here we suggest an initial focus for bioeconomy monitoring on the transition towards innovative bio-based products that not only may generate economic growth, but also often have a substituting function. We emphasize showcasing this kind of transition rather than increasing agricultural production or imports, which may not be directly connected to improving sustainability. Bioeconomy sustainability objectives, as formulated in [29], are termed “societal challenges” in the framework (Figure 1). The bioeconomy is expected to have a positive impact on these objectives, and we derive indicators for the challenges in the grey boxes (Figure 1) in this article.

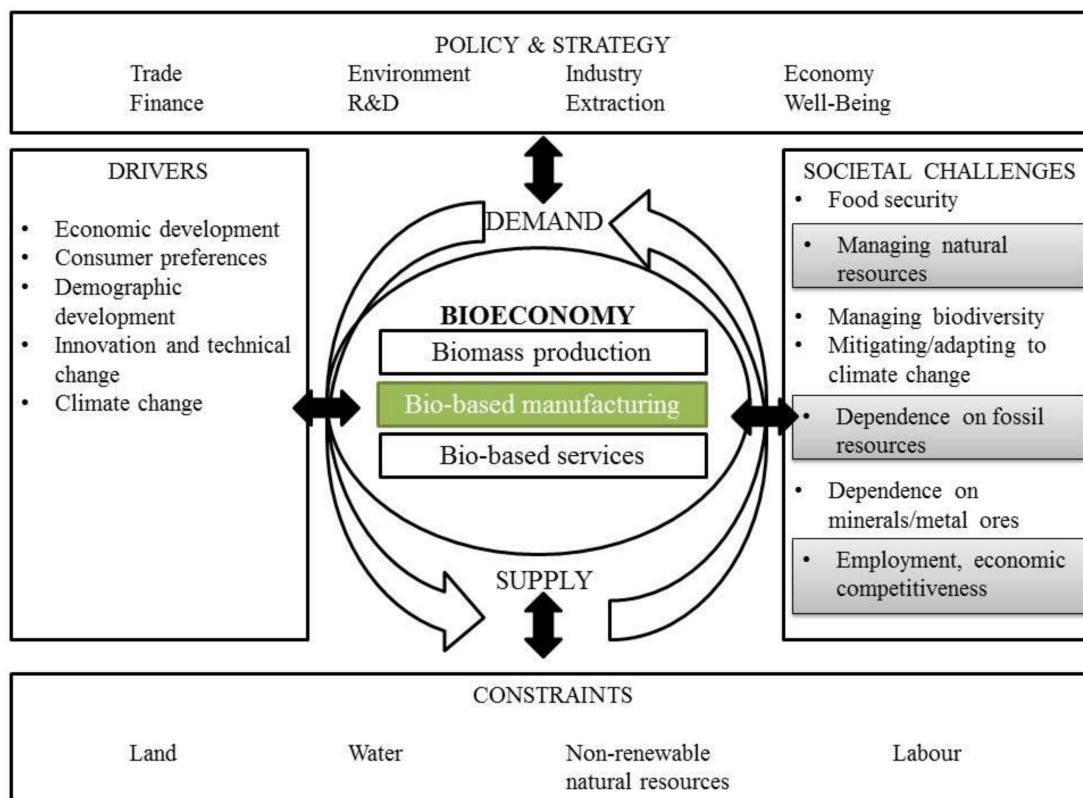


Figure 1. Bioeconomy Transition Framework (green represents the bioeconomy sector examined and gray the societal challenges, for which indicators are developed in this study). Source: Own illustration, adapted from [30].

2.1. Administrative and Sectoral Boundaries

As is common for economic classifications, the bioeconomy can be subdivided into three broad sectors: biomass production (primary sector), bio-based manufacturing (secondary sector), and related services, such as trade (tertiary sector). While in principle, all of these should be well represented in a monitoring system, the focus in this article is only on the manufacturing sector in Germany, which was chosen so as to investigate the complexity of value chains in the bioeconomy. Biomass production and the food sector have already been better covered by existing statistics than manufacturing because they are well delineated within economic classifications. The processes after first-stage processing are, however, more difficult to measure, as product and sectoral statistics do not list the types and amounts of resources used. Thus, in order to investigate the possibilities and limitations of indicators for such processing sectors, our case study deals with the manufacturing of surfactants, which is part of the chemical industry. We find that transitioning from a fossil- to a bio-based economy is a central objective in most bioeconomy strategies and that relevant substitution processes are occurring in the chemicals industry. Consequently, we examine this sector in our case study because, beside energy industries, chemical industries have been relying strongly on fossil fuels. The tertiary sector of trade and services related to bio-based products is not covered in this article but certainly deserves attention in any monitoring scheme. We focus our case study on Germany, because several ministries there are making a concerted effort to set up a bioeconomy monitoring scheme, taking the lead in this regard in Europe.

Bioeconomy developments are taking place at different levels, which define the boundaries of the analysis of monitoring systems. Depending on concrete monitoring goals, relevant levels may include the local, sectoral, national, regional, or global levels. For our empirical analysis, the level of the NACE classes was chosen because of our specific interest in comparing bioeconomy developments in different sectors. A class is defined as a group of products that are included in the NACE classification

system on the 4-digit level, which we selected because activities that are clearly attributable to the bioeconomy should be recorded there. While some industries are completely bio-based at the 2- or 3-digit levels—for example, the food, paper and pulp, and printed matter industries—others, such as the pharmaceutical or chemical industries, clearly have bio-based subsectors at best at the 4-digit level or even lower, meaning that bio-based shares have to be estimated. This study also provides a detailed assessment of the related 9-digit product codes. Most economic indicators are available at the 4-digit level but not lower.

2.2. Indicator Selection

The European Commission has proposed its own relevant, accepted, credible, easy, and robust (RACER) criteria for evaluating the usefulness of indicators in policymaking [31] (p. 308), which have been applied to resource use, resource efficiency, and environmental impact indicators lately [32]. For a future monitoring scheme, given the current limitations of data availability, we suggest a narrow set of basic indicators covering the economic, environmental, and innovation domains—each with two to four indicators—aiming to provide an overview of key bioeconomy transition dimensions. The initial selection of indicators for this study has been based on their relevance and practicality, with relevance being determined by an explicit linkage to the phenomenon under observation, meaning the bioeconomy and its effects. The relevant indicators should contribute towards understanding problems and identifying solutions for them. Practicality, or “easiness,” is taken here to mean that data and information collection is possible at low cost.

3. Indicator Methods and Data Sources

For our chosen economic indicators, “value added,” “turnover,” and “number of employees” were frequently mentioned and seemed to be of most interest to policymakers. To these, we added “foreign sales” and “investments.” All economic indicators were linked to the bioeconomy through the “bio-based share” indicator that showed bioeconomic growth in physical terms.

The economic–environmental indicators were examined to reveal trade-offs between contrary objectives, as growth in the value added of bio-based products may increase energy consumption if bio-based processes are more energy-intensive than fossil-based ones, for example. Combined indicators are valuable because they provide much information at a glance. If one part of the indicator stagnated, for example, the other part could compensate for this development with a strong increase. The environmental indicators chosen here refer to the objectives “managing natural resources” and “reducing dependence on fossil resources” in our BTF (Figure 1). When combined with economic indicators, they were “energy productivity,” “land productivity,” and “cost effectiveness in terms of fossil-resource savings.”

The innovation indicators for the bioeconomy should be useful for deriving information about whether and where innovation activities and outputs are likely to emerge and help to achieve desired positive impacts on societal goals. Hence, ideally, they should cover the whole innovation process, from inputs to outcomes/impact; however, the data availability for the latter is rather low [25], so we only included the indicators “publications” and “patents.” Together with the other chosen economic indicators, they were intended to map the objective of “improving economic competitiveness” in the BTF (Figure 1).

3.1. Bio-Based Share

As mentioned above, there are several industries at the 4-digit NACE classification level that belong only partially to the bioeconomy. For such cases, we developed an estimation method to determine the bio-based shares of respective industries by combining information from production and industry statistics. For manufactured goods, the annual production survey of the Federal Statistical Office of Germany provided the value and quantity of products intended for sale at the 9-digit level. We multiplied the production value of each good by its estimated bio-based share, as obtained from

the literature review and expert interviews, and summed the results up at the class level. Thus, the estimated bio-based production value results were given as a proportion of the total production value of a NACE class. Further economic indicators, such as employees and turnover, were only available in the official statistics at the NACE-class level. Under the simplifying assumption that production values per tonne are roughly the same within a NACE class, the same proportions for bio-based products could be assumed for these economic indicators as matches their share of the production values of the corresponding NACE class.

3.2. Number of Employees

The number of employees refers to the calculated labor force in the production of bio-based products. It is of high political interest, because it shows the contribution of the bioeconomy to the overall economic goal of full employment. The indicator was relevant for monitoring policy measures that aim at securing or creating employment opportunities, as well as measuring the impacts of new activities, such as technical innovation on the labor market. All economic data used for this study was collected from publications by the German Federal Statistical Office, and the number of employees can be found in the “Annual report for enterprises of manufacturing companies” [33].

3.3. Gross Value Added

Gross value added (GVA) was calculated as the total monetary value of the goods and services produced in the production process (production value) minus the value of the inputs used. At the macroeconomic level, it is included in the Gross National Product as the sum of all goods and services produced for final demand during a year. Related to individual economic sectors, such as the bioeconomy, it shows their overall economic importance. The indicator was relevant for the formulation and focusing of policies and other measures aiming at maximizing economic growth. The data for gross value added in the case study were taken from the publication “Cost structure survey in the manufacturing sector” [34].

3.4. Turnover

Turnover is the sum of the value of all products and services sold within a certain period of time and is a suitable indicator for representing the market share of a company or industry. It differs from production values due to changes in storage. The indicator may be used to better understand the economic importance of the various branches of the bioeconomy. Data for this indicator is available in the “Value added tax statistics” [35].

3.5. Foreign Sales

Foreign sales include goods and services sold to customers abroad or to exporters who export the goods without further processing. Foreign sales are an indicator of the international market share of a company or industry and, thus, also an indicator of its international competitiveness. The indicator was relevant for focusing policy measures and other activities related to export promotion. We drew data from the publication “Employment and turnover of enterprises in the manufacturing and mining industries and the extraction of stones and soils” [36].

3.6. Investment

Investment includes the outlay of financial funds for tangible investments (such as machinery), immaterial assets (such as software or patents), or financial investments (such as bonds or equity investments). It is decisive for both overall economic growth and the growth of individual companies, including those in the bioeconomy sector. As an indicator, investment statistics provide information about the development of medium- to long-term production capacities. Data for our case study came

from the publication “Investment survey of companies in the manufacturing and mining industries and extraction of stones and soils” [37].

3.7. Energy Consumption

Energy consumption is considered one of the main drivers of climate change, even with renewable sources gaining importance. While it is important to save fossil-energy sources by using more and more biogenic resources in products, this transition should not come at the cost of employing more energy-intensive production processes. A contribution of the bioeconomy to climate change mitigation is indicated if less energy is consumed over time. We calculated the energy consumption of a bio-based sector for a given year by multiplying the annual energy consumption of the whole sector by its bio-based share, including the use of natural and associated gas, district heating, and electricity in one sector, but not the material use of energy carriers or energy use in upstream sectors. Bio-based share is derived as described above for economic indicators, with sectoral energy consumption taken from German energy statistics [38]. We suggested combining this indicator with GVA to obtain the indicator “energy productivity,” which showed how much economic output could be generated from one energy unit, enabling the observation of relative and absolute decoupling. A growing GVA or decreasing energy consumption increased the energy productivity.

3.8. Land Footprint

Bioeconomy growth will very likely increase land usage compared to the current fossil-based economy. If such land is not used sustainably, however, it will become an indicator for a variety of environmental pressures, from biodiversity loss to soil degradation. We recommended including the land footprint of bio-based manufacturing sectors, showing how much land across the globe was used to produce biomass inputs. Our method started with an estimation of bio-based production on the 8-digit level and multiplied it by conversion rates for bio-based inputs, which were plant oils and animal fats in our case study. Based on the information from [39], we split the total amount into the demand for specific plant oils and, based on various literature sources, determined the amount of raw materials used. While material productivity might also be a valuable indicator in some contexts, we decided to go one step further by calculating land productivity based on global average factors for area required by FAOStat. We assumed that biomass was harvested due to producer demand in the selected sector and, thus, no allocation factors for by-products needed to be applied. The land footprint was also combined with the GVA, resulting in the indicator “land productivity.”

3.9. Fossil Resource Saving

One of the main arguments for supporting the transition to bioeconomy is its potential to reduce the reliance on fossil resources by substituting bio-based products for fossil-based products. As bio-based products may also rely on fossil resources as energy carriers or additional inputs, net savings needed to be calculated. Fossil resource saving (FRS) in a sector (s) showed how much crude oil, natural gas, and coal, in energy units, were saved due to the production of bio-based substitute goods (X_b) within a year. Fossil resource equivalents ($FRE_{b,f}$) were factors for fossil resource use along the supply chain of fossil-based and bio-based products, which we extracted from the life-cycle database ecoinvent (2017). Bio-based production was estimated based on bio-based shares, as described above. A more detailed description can be found in Jander and Grundmann (2019).

$$FRS_s = \sum_{b,f=1}^n X_b * (FRE_f - FRE_b) \quad (1)$$

The FRS was combined with the value of intermediate consumption, which was the value of inputs to a sector (s) or, put differently, turnover minus value added. We assumed that substitution might come at the cost of higher input prices, especially if increasing the demand for biomass resulted

in higher prices for these inputs, and value added might be reduced as a consequence. A growing FRS or decreasing value of inputs (i.e., costs) will cause an increase in FRS per €, which we called the “cost effectiveness in terms of fossil-resource savings” indicator.

3.10. Publications

The statistical analysis of scientific publications provided a means to monitor the performance of the science landscape over time. Here, we proposed the number of scientific publications in a sector of the bioeconomy in a country over time as an indicator, as data sources, literature, and citation databases were used, such as Scopus, Web of Science SciSearch, and Compendex. For our search strategy, we considered a combination of journals and books that could be completely attributed to the bioeconomy and a keyword search to identify further articles in other journals or books as appropriate.

3.11. Patents

Patent indicators are useful for monitoring the economically relevant results of innovation activities or measuring technological competitiveness in international comparison. Patent applications refer to inventions in the technical field that are new and for which an interest in industrial application is assumed. We proposed taking the absolute number of patents over time as an indicator for monitoring. Key questions arose here regarding the delineation of patent classes or keywords. In particular, it needed to be decided whether a patent search should solely focus on innovation for production or the use of biogenic resources or whether important input innovations, such as new agricultural machines, were to be included as well.

4. Results for Bio-Based Surfactants and Soaps

The manufacturing of surfactants and soaps is a core segment of oleochemicals that has seen an increase in bioeconomic activity in the past years, but for which little relevant information exists in comparison to other segments, such as biofuels. The indicators suggested in Section 3 were here applied to class 20.41 of the German Classification of Economic Activities (2008 edition), which is called the “Manufacture of soap and detergents, cleaning and polishing preparations.” The year 2015 was chosen, as data from the Federal Statistical Office and other data sources were relatively complete for this year. We focused on organic surface-active substances (anionic, cationic, and non-ionic) and soaps, which made up 75% of the production volume for sector 20.41 in 2015.

4.1. Past Transition and Implications

Table 2 displays our derivation of the proportion of bio-based surfactants and soaps in the production values of the whole NACE class 20.41. As explained in Highlights section, first, the bio-based shares in the production of surfactants (33%) and soaps (90%) were determined from a literature analysis and expert interviews. These shares were multiplied with the respective total production values and volumes of surfactants and soaps and summed up for NACE class 20.41, with the bio-based share of surfactants and soaps accounting for about 31% of the total production volume and 13% of the total production value.

In a second step, the calculated bio-based share in the production value was applied to the sector’s economic indicators. Based on the assumption that the bio-based share of production value was the same for all economic variables, the results shown in Table 3 were obtained for class 20.41. According to these estimations, 2782 people were employed in this sector in 2015, generating a gross value added of €470 m, a turnover of €904 m, and foreign sales of €355 m. At the same time, €45 m were invested in the bio-based part of NACE class 20.41.

Table 2. Derivation of the proportion of bio-based surfactants and soaps in the production volume and value of NACE class 20.41.

Production Code NACE Code	Designation	Production Volume			Production Value		
		Total Production (t)	Bio-Based Production (t)	Calculated Bio-Based Share of Production Volume	Total Production Value (m €)	Bio-Based Production Value (m €)	Calculated Bio-Based Share of Production Value
20.41.20	Surfactants	1,179,266	389,980	33%	1641	540	33%
20.41.31	Soaps	185,821	167,239	90%	198	178	90%
20.41	Manufacture of soap and detergents, cleaning and polishing preparations	1,828,060	557,219	31%	5356	718	13%

Source: Own calculations, based on [40].

Table 3. Results for economic indicators in the surfactant and soap industry.

Economic Indicator	NACE Class 20.41	Bio-Based Surfactants and Soaps
Number of employees	20,755	2782
Gross value added (m €)	3505	470
Turnover (m €)	6740	904
Foreign Sales (m €)	2646	355
Investments (m €)	333	45

Source: Own calculations, based on [40].

Whether bioeconomic growth is not only economically but also environmentally sound is shown here via the development of combined indicators, as explained in 3. One gigajoule used for the manufacturing of bio-based soaps and surfactants in 2015 generated, on average, €150 of value added. Meanwhile, energy consumption was 3,127 TJ, assuming a bio-based share of 31% and 10,238 TJ of process energy for the whole NACE class 20.41.

Regarding the resource of land, we found that the value added generated was €336 per ha. In total, the production of bio-based surfactants in 2015 required about 1.1 m ha for the cultivation of coconuts and palm oil fruits, whereas coconuts, palm oil fruits, soybeans, and sunflower seeds were grown on about 0.3 m ha for the production of soaps. The land requirements for soaps are much lower than for surfactants, because less palm kernel oil is used, which requires a much higher amount of raw materials per tonne of oil than the other raw materials. There is, however, much uncertainty in estimating the kinds of oils used. Anionic and non-ionic substances are produced from lauric and stearic acid, which can only be found in palm kernel and coconut oil [39]. We assumed a share of 50% of these oils. Other surfactants also have palm oil and animal fats as inputs. Soaps are produced from various oils [39], depending on the current market situation and desired product properties.

For every euro of input, 29 MJ were saved by producing bio-based surfactants and soaps in 2015. The most important bio-based substitute products in this sector were bio-based fatty alcohol ether sulfates, fatty alcohol sulfates, ethoxylated alcohol, and soaps. For fatty alcohol sulfates and ethoxylated alcohol, it was possible to determine the Fossil Resource Equivalents (FRE) for bio-based and fossil-based alternatives fromecoinvent, as well as for the coconut oil, palm kernel oil, and palm oil inputs. For fatty alcohol ether sulfates and fossil-based soaps, the same parameters as for fatty alcohol sulfates were used due to a lack of data. Based on our calculations, the Fossil Resource Saving (FRS) was 12,611 TJ in 2015. Assuming that soaps can also be produced from crude oil [39], bio-based soaps had the largest share in the savings, with 68%. Linear alkyl benzol acid is still completely fossil-based, and no bio-based alternative is currently being produced [39]. Cationic substances were not considered,

as they always have been bio-based and do not substitute a fossil-based alternative. While soaps have been traditionally bio-based as well, synthetic detergents (syndets) from fossil resources could replace bio-based soaps in the future, contributing to an opposite trend. They already have a market share of about 8% [41]. It is worth observing this “negative” substitution, because one kg of bio-based soap saves more fossil resources (51 MJ) than anionic and non-ionic surfactants (about 20 MJ).

4.2. Prospective Transition

For the prospective analysis, we have used the innovation indicators described in 3. Although the actual data were ex-post, it may be important for developing a prospective outlook, as current activities are undertaken with the expectation of further transitioning towards the bioeconomy and future returns. For patents and publications, we used worldwide numbers, as relevant markets were rather globalized and country-specific numbers fluctuated more heavily. Moreover, as proxy information for innovation output, for which reliable indicators were available, we assessed market developments and expectations from market studies. While market developments were not necessarily driven by new innovations, they indicated the market environment for the introduction and adoption of new products.

Our results are shown in Table 4. The publication indicators revealed a considerable increase, whereas patents have stagnated in recent years. This may be related to rather stagnant market development for bio-based surfactants, leading to a general decrease in innovative activities. According to a study commissioned by the FNR [39], the quantity of oils and fats in detergents, care products, and cleaning agents in Germany rose from about 589,000 tonnes in 2011 to around 599,000 tonnes in 2016. However, global market expectations are rather optimistic, with a forecast of global growth rates of around 6%–7% in the next five years [42]. An additional analysis for the development in Germany in the years 2010–2015 revealed significant activities in patenting and publication, occupying a position among the leading countries in this sector.

Table 4. Transnational* worldwide patents and publications for biosurfactants.

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Patents	1066	969	954	875	881	951	858	935	881	1067	890
publications	1854	1914	1961	2014	2150	2190	2292	2277	2315	2364	2433

Sources: WPINDEX (STN), SCISEARCH, COMPENDEX; * for the concept of transnational patents see [43].

5. Discussion and Recommendations

5.1. Findings

The selected indicators—developed and experimentally applied for measuring the progress of the bioeconomy in the sector of biobased surfactants—revealed a share of 13% of the production value of NACE class 20.41 and a share of 31% of the production volume for this sector. This finding indicated past and future growth in innovative, bio-based products and possibly the beginning of a transition from a fossil-based to a bio-based economy in this sector. A fossil resource saving of 12,611 TJ supported this observation. Linked to this development was a significant demand for biomass inputs and, ultimately, land, which was in line with previous research [44].

Our analysis of the innovation pipeline and market outlook indicated that there is considerable potential for future innovation that can fuel bio-based industries towards achieving higher growth rates and gaining market shares. However, such evolution cannot be taken for granted—an indication of which is the stagnation of patents filed, probably because of the declining market optimism among involved actors.

5.2. Methodological Challenges

We feel that our proposed indicators, as well as methods and data sources for calculation, provide an important step forward for monitoring bioeconomy progress. In order to guarantee sound and

reliable monitoring, however, more work is needed to further develop methods that increase the reliability of the monitoring results. As methodological shortcomings are frequently the result of insufficient data, we recommend the extension of data sources in 5.3.

Clear delineation between the emerging bioeconomy and other parts of the economy is still missing with regard to relevant PRODCOM (“PRODUCTION COMMUNAUTAIRE”) codes, patents, or publication searches, for example. Although the setting of boundaries appeared to be rather straightforward in our case study, in terms of the identification of relevant statistical codes and estimating bio-based shares, the critical assessment of other research and harmonization with other studies is needed. In [24], for example, all products that use biogenic resources in order to substitute fossil-based products were considered in the analysis. For the case of surfactants and soaps, this approach omits cationic substances, as these do not have a substituting function. Meanwhile, [11] considered all industries that have biological inputs, whereas [45] did not further specify relevant bioeconomy sectors in their Driver-Pressure-State-Impact-Response framework.

The bio-based share of a smaller part of NACE class 20.41, meaning only surfactants and soaps, was much higher for us, at 13%, than as found by [11], who calculated a bio-based share of 4% of input value. This illustrates a range of results depending on the methods employed. [23], who further developed the method used by [11], underlined this possibly wide range by finding a bio-based share from 2.6% to 13.5% for this NACE class. Both methods, with one relying on official data and the other relying on expert estimates, currently suffer from non-transparent and arbitrary procedures in the derivation of bio-based shares.

One limitation of the current approach, as well as in many other economic assessments of the bioeconomy, is that all economic indicators are estimated proportionally to the bio-based share of resource use. However, there is uncertainty about whether the bio-based share is truly the same for all indicators. Some industries may, in general, be more export-oriented than others, especially with respect to foreign sales. Hence, the bio-based share could be different with respect to turnover, on the one hand, and foreign sales on the other. The same could be true for investment. The goal of developing bio-based production could require more investment than traditional production, meaning that the bio-based share of investment could be higher than investment in the traditional part of the industry. While this assumption can often be considered as a best guess for some indicators, such as turnover, the value added is probably correlated less with resource use. Bio-based products may have high value added in niches, such as high-price cosmetics, combined with relatively low resource use. This difference can be even more pronounced for environmental indicators. With top-down bio-based share assumptions, important characteristics may be overlooked, such as different energy usage for conventional and bio-based products. In our case study, additional information from ecoinvent regarding per-tonne energy consumption was not informative, as there was no significant difference between bio-based and fossil-based surfactants, whereas in other sectors, such as transport fuels, the proportionality assumption is untenable.

For the innovation indicators used in this article, the identification of bio-based relevant publications or patents is more straight-forward, as they can be identified on a much higher granularity level. Nevertheless, in some cases, bio-based patents can still be separately identified, as there is no reference to the feedstock in the international patent codes. Related to this, there are not yet any lists for codes or keywords for the bioeconomy for patents and publications that are widely accepted.

Overall, our case study shows that investigating the market and resource flows of bio-based products on a disaggregated level can be very informative and combines well with existing data sources. Nevertheless, great uncertainties still exist concerning biomass inputs and origins for surfactants and soaps. For example, for want of more specific information, we have assumed the shares of different oils and fats in terms of input volumes and we have used worldwide average values for area requirements. These uncertainties call for an analysis of the dependence of results on the kind of raw materials used and on production conditions in different regions.

5.3. Recommendations

A requirement for goal-oriented monitoring of the bioeconomy is that potential users agree and clearly define the objectives of the system. What are the boundaries of the bioeconomy, and which aspects of it should be observable through monitoring? The framework suggested in Section 2 includes many possible bioeconomy boundaries for scientific analysis, depending on the monitoring objectives. We recommend a focus on the most interesting and agreed upon objectives, such as fossil resource substitution, the use of natural resources, such as land and water by the bioeconomy, and the promotion of a certain biogenic resource for new bioeconomy monitoring schemes with limited financial resources. In the beginning, it would be useful from a methodological point of view to focus on the manufacturing sectors where bio-based (substitute) products are currently gaining market shares, instead of trying to coarsely outline the whole bioeconomy, however, it is defined with methods still in their infancy that rely on official data, which are not at all designed to unambiguously identify bio-based products. Analyzing sectors in depth allows targeted resource allocation and more sustainable production. From a resource economic and political point of view, it might be useful to focus first on sectors with a particularly high use of resources. Over time, as data collection becomes more refined and methods more mature and transparent, more indicators and sectors could be gradually introduced to the monitoring scheme. Regarding matters of consistency and feasible workload, more detailed official production statistics are needed to delineate bio-based products. However, this would require changes in laws and intensive coordination between statistical agencies at different levels (regional, national, European).

Regarding bio-based industry shares, we recommend refining the estimation methods before delivering indicators for the whole bioeconomy. We agree with [23] that, given insufficient official data for bio-based product groups, transparently presented expert estimates should play an important role. The identification and selection of experts and key informers is crucial in this regard and the use of participatory methods should be improved in future analyses. This would allow the monitoring of the dynamics of bioeconomy developments if regular and precise updates on bio-based inputs, the raw materials used, and their origins were available.

As long as no significant improvements in the quality and quantity of official data are achieved, analysis and monitoring activities have to rely on complementary data for bio-based products. Expert opinion may not only verify bio-based shares, but also assumptions, such as proportionality between bio-based shares and suggested indicators. Environmental indicators could be informed by lifecycle data from respective data bases. In our view, the data from the life cycle assessment (LCA) can only inform us about relative differences and not about absolute energy use because, first, not all processes in a sector are included in existing data bases, and, second, representative products, as analyzed in the literature, for a given year might overestimate efficiency. Statistical data based on annual surveys is more current, even though estimation procedures are also necessary. A combination of economic with environmental indicators is currently possible using LCA data, if no other information is available from surveys. In-depth material flow and market studies should be regularly commissioned along with further, regionally specific LCA studies of new bio-based processes. Given the resource bases of the bioeconomy and their rather decentralized production patterns, the local level should constitute the reference or basis of validation for nearly any analysis and monitoring effort, and any monitoring results should be validated via information on the local and product levels. In the long term, the German survey “Materials and Goods Received” could be extended to include more disaggregate input groups, meaning not just agricultural inputs, but, specifically, cereals and oil crops, and receiving industries could also be further disaggregated in some cases, such as chemicals. Including these steps and input groups would enable a more detailed input–output table for Germany—as it is common for Japan, Australia, and the USA—and more reliable analyses of the FRS indicator, for example. For innovation indicators, similar issues apply. While in the long term, it would be appropriate to further develop codes and classifications that enable the identification of bio-based innovations; in the short term,

efforts towards a common list of keywords and patent codes based on current classifications would be helpful.

Additional indicators may be appropriate for obtaining a more comprehensive overview in the future, such as with social or further economic, ecological, or innovation indicators. As indicated above, we do not provide a complete list of useful indicators, but have instead focused on presenting those with rather good data availability. Nevertheless, it should be noted that in an extensive study, the authors of this article have empirically derived a total of seventeen economic indicators for surfactants and soaps, including indicators, such as gross production value and domestic sales [19]. This study also includes a list of further environmental sustainability indicators that could be linked to the bioeconomy. Two approaches were suggested: using “top-down” national sustainable development indicators, as measured by the German Statistical Office, such as air emissions and phosphorus in water, and using “bottom-up” product data from life cycle inventories, such as the use of pesticides and nitrogen fertilizer. More have been suggested in [18] (p. 10). A further interesting area of study is circular bioeconomy, which is increasingly studied but has hardly addressed indicator development and sectoral analyses so far [46]. Bioplastics, solvents, lubricants, fabrics, fine chemicals, and insulation material have been identified in a multi-criteria decision analysis as significant sectors in studying the circular economy [47]. Extensive combination options are also possible. For example, labor productivity can be calculated from the combination of gross value added and employed persons. A combination with environmental indicators would also be conceivable for individual economic sectors, such as the turnover achieved per hectare of forest land in the forestry sector. While we suggest comparing economic sectors within a country, applying spatially explicit indicators at the local, regional, and global level would provide important information on drivers and outcomes on the respective level.

Regarding the innovation indicators, the patent and publication indicators we used are only early stages of the innovation process. There are still clear data gaps in the outcome and impact indicators. Current government surveys do not provide adequate boundary setting for analyzing the bioeconomy. This could be improved in the future by, for example, conducting an explicit survey regarding the bioeconomy or through adding another item in the European Community Innovation Survey (CIS) asking whether responding firms are active in the bioeconomy or not or by adding questions similar to those concerning environmental innovation, which is a topic in the CIS every few years [48].

Furthermore, in order to provide more decision-relevant information for public and private actors, greater focus may be placed on the ex-ante assessment of innovation and innovation potentials. There have been some important studies in the past in this regard, but more comprehensive coverage beyond the lists of examples of single innovations is crucial. Moreover, certain impacts, including the potential prices and cost structure for actors, potential substitution rates of fossil-based products, or required land use, may be important information that can be gathered using a systematic approach. In addition, the integration of such indicators into a model-based forward-looking analysis (e.g., [49,50]) may provide further insights regarding the potential diffusion and economic and environmental impacts of the bioeconomy.

6. Summary and Conclusions

With this article, we wish to contribute towards the development and measurement of relevant indicators for the economic and environmental impacts of bioeconomies. We have discussed approaches, derived indicators, and applied them to monitor developments in surfactant production in Germany. New indicators and analytical frameworks for the investigation of transformations within and the monitoring of bioeconomy innovations have also been discussed. In summary, we suggest that our results contribute towards creating a basis for forecasting, future scenario analysis, and impact assessment of bioeconomy developments.

We have also identified shortcomings in the ways official statistics are generated that are jeopardizing the intention and relevance of transition-monitoring systems in general and of our proposed indicators in particular, including significant weaknesses in the existing data and information

base regarding the bioeconomy in Germany. To our knowledge, the case of Germany is not unique, however, as the monitoring efforts in other parts of the world are also affected by such limitations. The identification and evaluation of options and strategies to improve information bases should be given high priority at all levels involved in the implementation of bioeconomy monitoring systems. A short-term strategy proposed here is the integration of further data sources, which can refine the results and extend the assessments to other areas of the economy. In addition to possibly having positive impacts on decision making in practice, this may also enable a more advanced ex-ante analysis, using them as tool models based on input–output tables, for example. Future research should also address the integration of indicators into monitoring systems that reveal otherwise largely neglected social impacts. The limitations of this study also make it necessary to further examine the validity and applicability of the indicators and frameworks for other sectors and the bioeconomy as a whole. This step must be accompanied by the review of the meaning of indicators for research activities and their relevance in view of the intentions of decision-makers in practice. The development of several bioeconomy monitoring systems can be expected in the medium term as a result of a number of national, European, and global initiatives. This calls for the proper coordination of activities and even the harmonization of approaches and tools at all levels to enable synergies and facilitate exchange and comparison of results.

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