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Inter-connected challenges: an overview of bioeconomy in Europe

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Abstract

The use of renewable biological resources from the land and sea to produce food, materials and energy is one of the potential solutions to implement the green transition. The bioeconomy is developed in Europe, however it shows a different trend in several countries. The methodology used in this paper is based on multicriteria decision analysis and considers three parameters as criteria: workers, turnover and value added. This work investigates the bioeconomy sectors in 28 European countries using the socio-economic indicator for the bioeconomy (SEIB). We provide useful data for all stakeholders and propose a quantitative analysis emphasizing the contribution of each bio-based sector. The results show that Ireland is ahead of the Netherlands and Denmark in the SEIB for all sectors and leads in the SEIB for manufacturing and bio-energy sectors followed by Denmark. The differences with other European countries are significant. Some countries present a rather weak situation (Slovakia and Malta). The values of the SEIB are mainly linked to performance in two macro sectors: (a) agriculture and (b) manufacture of food, beverages and tobacco. The decomposition analysis highlights the performance of each country according to the socio-economic parameter and the bioeconomy sectors, and it is highlighted how performance monitoring allows for the identification of corrective actions. Some policy implications are proposed to support the development of bioeconomy sectors by targeting inter-connected challenges that aim to foster sustainability.

1. Introduction

The issue of sustainability is on the agenda of many countries and along with other phenomena such as the pandemic and the conflict in Ukraine highlight that the challenges of civil society are multiple. A global challenge requires secure and cooperative partnerships among governments (Xu *et al* 2021). Sustainability assessments of the G20, which account for more than 80% of global consumption of materials, fuel, and food, allow for capturing relationships among several key variables, such as renewable energy, improved supply chains, and replacement of high-impact materials (Cabernard *et al* 2022).

The theme of sustainable development goals (SDGs) has gained prominence (Shuai *et al* 2021) and within the literature, bioeconomy can contribute to the achievement of some of these SDGs. Particular attention should be paid to socio-economic targets (Maksymiv *et al* 2021) in order to foster economic development, access to basic services, and sustainable consumption (Calicioglu and Bogdanski 2021). A high level of corporate social responsibility, the use of sustainable biomass in the production process, and the use of biotechnology are all identified as enablers toward sustainability (Heimann 2019).

'With its cross-cutting nature, the Bioeconomy offers a unique opportunity to address complex and inter-connected challenges, while achieving economic growth' (European Commission 2022b).

The bioeconomy is defined by the European Commission as an economy that uses renewable biological resources from the land and sea (e.g. animals, crops, fish, forests, and microorganisms) to produce energy, food, and materials (European Commission 2018). Together with the 2018 EU Bioeconomy

Strategy, the European Green Deal emphasizes the relevance of the bioeconomy and the strong correlation between the concepts of bioeconomy and circular economy (Kardung *et al* 2021). In this way, there is need to underlie the strategic impact that the circular bioeconomy can play in achieving the SDGs (D'Adamo *et al* 2021). The literature places great emphasis on studying the bioeconomy in Europe (Ols and Bontemps 2021), evaluating effects on land use spill overs (Bruckner *et al* 2019), and the need to conduct a systematic review of methods and results (Hurmekoski *et al* 2021, Dima *et al* 2022).

The bioeconomy is a new industrial paradigm that aims to address significant societal, ecological, and economic problems such resource depletion, food insecurity, and climate change (Wydra 2020). The bioeconomy has tremendous potential to foster sustainable economic growth and is capable of creating job opportunities in rural and industrial areas (Vivien *et al* 2019). The bioeconomy is sustainable when certain conditions are met: (a) sustainability of processes and products; (b) sustainability of the resource base and (c) circular processes of material flows (Gawel *et al* 2019).

The bioeconomy can enhance the resilience of bio-based, food, and energy systems in the post-pandemic era (Galanakis *et al* 2022). The literature emphasizes the need for studies that focus on the environmental contrast associated with bio-based versus fossil-based products (Jander 2022) and the calculation of the bio-based share (D'Adamo *et al* 2022a).

The literature has focused for some times on all three dimensions of sustainability, both in a holystic way (Egenolf and Bringezu 2019), or considering them separately—environmental (Brizga *et al* 2019), socio-economic (Jarosch *et al* 2020), and economic-environmental (Jander *et al* 2020). However, a paradigm shift is needed, in which all stakeholders make their contributions with a view to developing a sustainable community (D'Adamo and Sassanelli 2022).

The topic is particularly felt in Europe, and the bioeconomy requires a broadening of vision beyond stakeholder positions and policy debates (Eversberg and Fritz 2022), but assessing the consistency among different policies (Befort 2020).

The literature from which the gap emerges is one that aims to identify metrics to monitor the development of the bioeconomy (O'Brien *et al* 2017), and socio-economic issues need to be explored (Sanz-Hernández *et al* 2019). The bioeconomy consists of several sectors, and monitoring systems are developed to assess their socio-economic progress in Europe (Ronzon *et al* 2020). Specifically, these systems are based on three parameters: (a) turnover; (b) value added and (c) workers (Ronzon and M'Barek 2018). A socio-economic indicator for the bioeconomy (SEIB) has been proposed to aggregate these parameters through multi-criteria decision analysis (MCDA) providing separate assessments for primary and innovative sectors (D'Adamo *et al* 2020).

Given the relevance of the bioeconomy in the European policy agenda, it is crucial to have a transparent and consistent monitoring framework that considers the socio-economic progress of bioeconomy activities (Ronzon *et al* 2022), identifying drivers and opportunities (D'Adamo *et al* 2022b). This work aims to fill that gap. For this reason, the SEIB is calculated at macro level by applying the latest available data in Europe. It is calculated for all sectors and for manufacturing and bio-energy sectors in both baseline and alternative scenarios. A decomposition analysis according to socio-economic parameters and bioeconomy sectors is then provided in order to capture useful insights and policy implications.

The work is structured as follows: section 2 proposes the methodology and the data used, section 3 concerns the results achieved and their implications. Elements and perspectives for discussion are proposed in section 4 and conclusions are presented in section 5.

2. Materials and methods

The MCDA is an analysis that allows for the comparison of different alternatives by means of certain criteria. It is based on the product between the measurement of a performance (scoring criteria) and one of relevance (weighting criteria). The strength of this methodology is also its flexibility and suitability to use specific indicators as criteria (Kumar *et al* 2017). An approach taken up by several authors to compare the performance of different countries, useful not only for ranking but also for identifying actions to be taken (Antanasijević *et al* 2017, Vavrek and Chovancová 2019). In particular, the MCDA approach is suitable for measuring, in a comparative way, developments in terms of sustainability (Su *et al* 2020, D'Adamo *et al* 2022a).

2.1. A SEIB

The SEIB is an indicator that measures the impact of the bioeconomy with respect to economic and social dimensions, not directly assessing the environmental component (D'Adamo *et al* 2020). Thus it cannot be included within the sustainability indicators. However, it makes its contribution to sustainability because it measures the impact of bio-based sectors that using environmentally friendly sources (Capasso and Klitkou 2020).

Two forms of the SEIB were provided to define the impact of both primary and innovative sectors, and the SEIB was developed using MCDA:

- SEIB for all sectors.
- SEIB for manufacturing and bio-energy sectors.

The difference is that the second version excludes primary sectors, while the first includes all sectors of the bioeconomy. This approach does not aim to penalize primary sectors considered relevant (Asada and Stern 2018), but to broaden the overview toward all sectors by measuring performance at the level of each individual country. The SEIB calculation is based on two levels, in which we initially calculate the value of the SEIB for a specific bio-based sector (SK)—(equation (1)) and then aggregate all sectors (equation (2)). The variable related to bio-based sectors is K, which varies from 1 to N (number of sectors considered) and a specific and dimensionless SEIB is obtained for each alternative (country–C).

Thus the literature has identified two different levels, where the first level allows for the comparison of several alternatives by evaluating appropriate criteria. The result is a ranking among alternatives concerning a specific sector. This specific value also depends on the weight that this sector has within the bioeconomy. Finally, since the bioeconomy is composed of N sectors, the second level of analysis involves aggregating the SEIBs of each sector in order to have a unique result that identifies a ranking among different alternatives. The SEIB can refer to different territorial realities and in this work, 28 European countries are considered (considering that a pre-Brexit period was considered).

SEIB is obtained by combining three variables. The first concerns the value of the socio-economic criteria for each sector (VP). The second regards the weight of the socio-economic criteria for each sector (WP). Finally, it is proposed the weight of the bio-based sectors among all sectors (WS). It should be noted that the number of parameters (turnover, value added and workers) considered is 3 (P1, P2 and P3) according to section 1. This choice aims to consider the socio-economic values available in the JRC-Bioeconomics dataset (European Commission 2019), without penalizing the environmental component enhanced by the presence of bio-based sectors (D'Adamo *et al* 2022a):

$$\begin{aligned}\mathrm{SEIB}_{\mathrm{SK-(C)}} = {} & \mathrm{VP}_{\mathrm{SK-(C)-P1}} \times \mathrm{WP}_{\mathrm{SK-P1}} \times \mathrm{WS}_{\mathrm{SK-P1}} \\ & + \mathrm{VP}_{\mathrm{SK-(C)-P2}} \times \mathrm{WP}_{\mathrm{SK-P2}} \times \mathrm{WS}_{\mathrm{SK-P2}} \\ & + \mathrm{VP}_{\mathrm{SK-(C)-P3}} \times \mathrm{WP}_{\mathrm{SK-P3}} \times \mathrm{WS}_{\mathrm{SK-P3}}\end{aligned} \tag{1}$$

$$\mathrm{SEIB}_{\mathrm{(C)}} = \sum\nolimits_{K=1}^{N} \mathrm{SEIB}_{\mathrm{SK-(C)}} \tag{2}$$

in which $\mathrm{SEIB}_{\mathrm{SK-(C)}}$ is the SEIB calculated for the bio-based sector SK and country C; $\mathrm{VP}_{\mathrm{SK-©-P1}}$ is the value of turnover in the bio-based sector SK and for country C; $\mathrm{WP}_{\mathrm{SK-P1}}$ measures the weight of turnover for the same bio-based sector SK and $\mathrm{WS}_{\mathrm{SK-P1}}$ measures the weight of turnover for the bio-based sector SK. Evidently, these last components cannot be influenced by the country under consideration. The product between these three components measures the impact of turnover (P1), and should be repeated in the same way for the other two criteria: $\mathrm{VP}_{\mathrm{SK-C-P2}}$ is the value of value added in the bio-based sector SK and for country C; $\mathrm{WP}_{\mathrm{SK-P2}}$ measures the weight of value added for the bio-based sector SK; $\mathrm{WS}_{\mathrm{SK-P2}}$ measures the weight of value added for the bio-based sector SK; $\mathrm{VP}_{\mathrm{SK-C-P3}}$ is the value of workers in the bio-based sector SK and for country C; $\mathrm{WP}_{\mathrm{SK-P3}}$ measures the weight of workers for the bio-based sector SK; $\mathrm{WS}_{\mathrm{SK-P3}}$ measures the weight of workers for the bio-based sector SK. The sum of the contributions associated with each of the three parameters makes it possible to calculate the SEIB for a specific sector. The sum of all these values determines the overall SEIB for a specific country ($\mathrm{SEIB}_{\mathrm{(C)}}$).

The sectors considered in this work follow the guidance provided by the classification of economic activities of the European Community (NACE rev. 2) and are then grouped into ten macro sectors (Ronzon and M'Barek 2018). In particular, the categories are updated according to the JRC-Bioeconomics dataset (European Commission 2019) including 18 micro sectors:

- $K = 1 \rightarrow$ Agriculture (A01);
- $K = 2 \rightarrow$ Forestry (A02);
- $K = 3 \rightarrow$ Fishing and aquaculture (A03);
- $K = 4 \rightarrow$ Manufacture of food, beverages and tobacco (comprising Manufacture of food (C10), Manufacture of beverages (C11) and Manufacture of tobacco (C12));
- $K = 5 \rightarrow$ Manufacture of bio-based textiles (comprising Manufacture of textiles (bC13), Manufacture of wearing apparel (bC14) and Manufacture of leather (bC15));
- $K = 6 \rightarrow$ Manufacture of wood products and furniture (comprising Manufacture of wood products (bC16) and Manufacture of furniture (bC31));
- $K = 7 \rightarrow$ Manufacture of paper (bC17);
- $K = 8 \rightarrow$ Manufacture of bio-based chemicals, pharmaceuticals, plastics and rubber (excluding biofuels) (comprising Manufacture of chemicals (excluding biofuels) (bchem), Manufacture of pharmaceuticals (bC21) and Manufacture of bio-based plastics and rubber (bC22));
- $K = 9 \rightarrow$ Manufacture of liquid biofuels (comprising Manufacture of bioethanol (Bioeth) and Manufacture of biodiesel (Biod)) and
- $K = 10 \rightarrow$ Production of bio-electricity (bD3511).

Finally, it should be pointed out that the difference between the two versions of the SEIB consists in excluding three macro-sectors ($K = 1$, $K = 2$ and $K = 3$) in the version SEIB for manufacturing and bio-energy sectors.

2.2. Input data

The values used in this work were extracted from the JRC-Bioeconomics dataset (European Commission

Table 1. Socio-economic parameters of the European bioeconomy in 2019. Adapted by (European Commission 2019). Workers expressed as number of persons employed; turnover and value added measured in million €.

Sectors	Workers	Turnover	Value added
$K = 1$	9188 740	470 003	205 372
$K = 2$	536 800	50 989	25 013
$K = 3$	178 740	14 760	6387
$K = 4$	5094 929	1277 664	270 416
$K = 5$	770 530	89 271	26 571
$K = 6$	1460 249	191 573	55 430
$K = 7$	696 283	204 485	52 309
$K = 8$	522 837	213 986	71 226
$K = 9$	26 652	14 323	3145
$K = 10$	34 329	35 410	6349
Total	18 510 089	2562 465	697 205

2019) and the most up-to-date data for 2019 were considered. In particular, 840 data were managed for this year, obtained from the product of the 3 parameters, the 10 macro sectors and the 28 alternatives. It should be pointed out that the values for EU28 were calculated by adding the contributions from the individual countries—table 1.

The estimated data show the number of workers at 18.5 million, turnover at 2.56 billion € and value added at factor cost at 697 million €. These values show an increasing trend compared to 2017, with turnover showing the most significant growth at 7.8%, followed by 5.6% associated with value added and 4.9% of the number of workers.

2.2.1. The value of the socio-economic parameters for each sector

All VPs were obtained by normalizing the absolute values for the population (referring to the year 2019) in order to make the data homogeneous according to literature (Szopik-Depczyńska *et al* 2018, Barbier and Burgess 2019). A 0–1 range approach was considered, in which values at the extremes were associated with the worst and best performance, respectively. In addition, intermediate values were calculated by linear interpolation. Value analysis is conducted at the macro-sector level. This represents a different approach than the original SEIB (D'Adamo *et al* 2020), where an analysis of values was conducted at the micro sector level. For example, for $K = 1$ consisting only of the A01 code, no differences are recorded between macro and micro level. Instead, if we use a micro level both codes bC16 and bC31 are evaluated individually, while they are aggregated in the macro one.

Table 2 shows the top countries for each macro-sector and socio-economic parameter.

2.2.2. The weight of the socio-economic parameters for each sector

The weights associated with the parameters are obtained by a survey among experts (academicians and researchers) with long-term expertise in the bioeconomy. In order to compare the results of this work with those reported in the literature (D'Adamo *et al* 2020), it was chosen to consider the same weights. Consequently, all WPs are identified by literature. This choice is also justified since they were collected in a recent time frame and were identified by a panel of experts—table 3. However, this work will also consider an alternative scenario in which the weight among the three parameters will be chosen the same for all sectors.

Table 2. Top position of European MSs.

Sectors	Workers	Turnover	Value added
$K = 1$	Romania	Netherlands	Netherlands
$K = 2$	Latvia	Finland	Finland
$K = 3$	Greece	Malta	Greece
$K = 4$	Cyprus	Denmark	Ireland
$K = 5$	Portugal	Italy	Italy
$K = 6$	Estonia	Netherlands	Estonia
$K = 7$	Finland	Netherlands	Finland
$K = 8$	Denmark	Netherlands	Ireland
$K = 9$	Finland	Finland	Finland
$K = 10$	United Kingdom	United Kingdom	Denmark

Table 3. Normalized weights of the socio-economic parameters. Adapted by (D'Adamo *et al* 2020).

Sectors	Workers	Turnover	Value added
$K = 1$	0.289	0.368	0.343
$K = 2$	0.321	0.352	0.327
$K = 3$	0.323	0.347	0.330
$K = 4$	0.318	0.347	0.335
$K = 5$	0.332	0.337	0.330
$K = 6$	0.321	0.345	0.334
$K = 7$	0.305	0.359	0.336
$K = 8$	0.307	0.355	0.338
$K = 9$	0.315	0.356	0.329
$K = 10$	0.319	0.353	0.328

The distribution of weights among the parameters in the order of the three parameters does not see significant variations. In fact, turnover is always placed as the most important and workers as the least important (only in $K = 5$ is it better than value added). However, it should be noted that the reported numerical values show important variations. Turnover reaches its highest value (0.368) in the $K = 1$ sector and the same is true for value added (0.343). At the same time for this macro sector workers has the lowest value (0.289). As highlighted earlier the $K = 5$ sector is the one that workers has the highest value with 0.332 and the lowest value of turnover with 0.337. In contrast, the lowest value added value is 0.327 in the macro sector $K = 2$.

2.2.3. The weight of the bio-based sector

The weight of sectors within the bioeconomy can be calculated using statistical data. Starting from the

Table 4. Percentage distribution of the European bioeconomy sectors in 2019. Adapted by (European Commission 2019).

Sectors	Workers	Turnover	Value added
$K = 1$	0.497	0.183	0.284
$K = 2$	0.029	0.020	0.035
$K = 3$	0.010	0.006	0.009
$K = 4$	0.275	0.499	0.374
$K = 5$	0.042	0.035	0.037
$K = 6$	0.079	0.075	0.077
$K = 7$	0.038	0.080	0.072
$K = 8$	0.028	0.084	0.099
$K = 9$	0.001	0.006	0.004
$K = 10$	0.002	0.014	0.009

overall values shown in table 1 we can see the decomposition that shows the $K = 4$ macro sector in first place for both turnover and value added parameters. In contrast, the $K = 1$ macro sector prevails in the workers parameter. Table 4 proposes WS of the bio-based sector according to the parameter considered.

The data that emerges from the distribution of the weights is the presence of these two sectors that affect very significantly compared to all the others: (a) agriculture and (b) manufacture of food beverages and tobacco. Their contribution is 77% considering workers and 68% for the other two parameters (turnover and value added).

Table 5. SEIB for all sectors in 2019.

Ranking	Country	Value
1	Ireland	0.576
2	Netherlands	0.520
3	Denmark	0.503
4	Belgium	0.358
5	Spain	0.356
6	France	0.350
7	Austria	0.345
8	Lithuania	0.326
9	Italy	0.320
10	Greece	0.313
	EU 28	0.300
11	Germany	0.291
12	Cyprus	0.288
13	Poland	0.281
14	Romania	0.277
15	Finland	0.275
16	Portugal	0.267
17	Bulgaria	0.264
18	Latvia	0.238
19	Estonia	0.237
20	Croatia	0.236
21	Hungary	0.234
22	Sweden	0.227
23	Slovenia	0.212
24	Czechia	0.198
25	United Kingdom	0.141
26	Luxembourg	0.134
27	Slovakia	0.089
28	Malta	0.054

3. Results

The main objective of a MCDA is to propose a ranking among alternatives that can analyze performance. The values obtained can be read in multiple ways in order to capture the different points of interest.

3.1. The assessment of the SEIB for all sectors—baseline scenario

The first step of our analysis is the calculation of the SEIB in the baseline scenario, when all sectors are included. It emerges that there are three countries that have a very significant performance (table 5): Ireland leads the ranking with 0.576 followed by Netherlands and Denmark with 0.520 and 0.503, respectively. In fact, Belgium, which ranks fourth, has a value of 0.358 and, together with six other countries, is above the European average of 0.300. Below the average are 18 countries, among which the situation is very critical for the United Kingdom, Luxembourg, Slovakia and Malta (figure 1), with values ranging from 0.141 to 0.054.

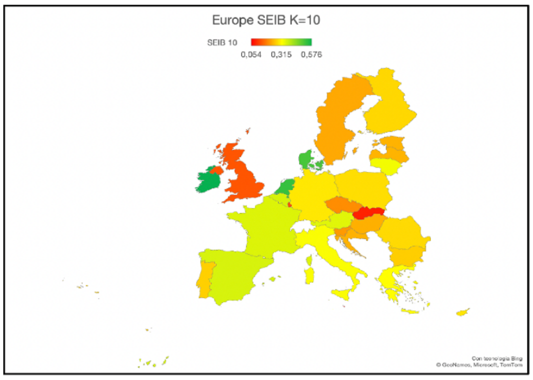

Figure 1. A graphical representation of the SEIB for all sectors in 2019.

3.2. The assessment of the SEIB for manufacturing and bio-energy sectors—baseline scenario

The second step of the analysis is to calculate the SEIB for manufacturing and bio-energy sectors and to highlight any deviations from the previous version of the SEIB. If the delta proposed in table 6 has a negative sign, it shows that the weight of the primary sectors is very significant for that country. Ireland has a value of 0.666 and confirms its first position, followed this time by Denmark with 0.573. For this version of the SEIB, we find the Netherlands again among the first three countries, but with a value that is more detached and close to the other ten countries which are above the European average of 0.344 (figure 2). Only three European countries show a reduction in value. Among these, the Netherlands shows a slight decrease, while the reductions in Greece and Romania

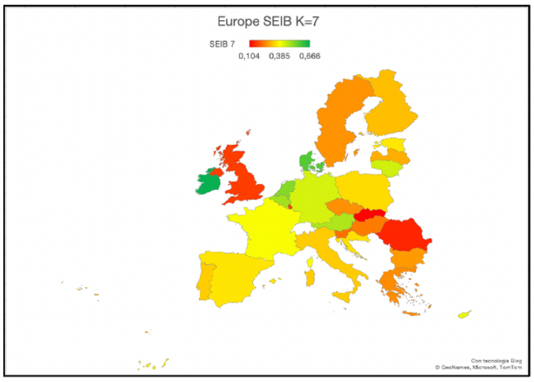

Figure 2. A graphical representation of the SEIB for manufacturing and bio-energy sectors in 2019.

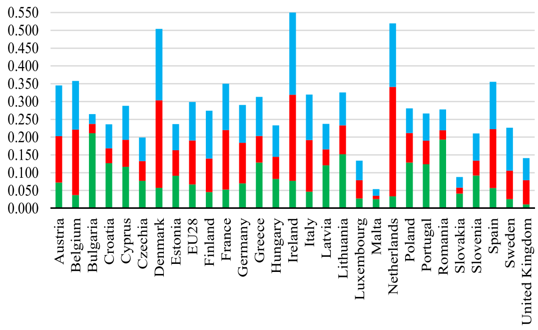

Figure 3. A decomposition analysis of SEIB for all sectors in 2019 as a function of socioeconomic parameters.

Table 6. SEIB for manufacturing and bio-energy sectors in 2019. Delta measures the difference between SEIB for manufacturing and bio-energy sectors and SEIB for all sectors.

Ranking	Country	Value	Delta
1	Ireland	0.666	0.090
2	Denmark	0.573	0.070
3	Netherlands	0.519	−0.001
4	Belgium	0.488	0.130
5	Austria	0.474	0.129
6	Lithuania	0.437	0.111
7	Germany	0.430	0.139
8	Cyprus	0.412	0.123
9	France	0.391	0.041
10	Estonia	0.360	0.123
11	Spain	0.357	0.001
12	Croatia	0.351	0.114
13	Poland	0.346	0.065
	EU 28	0.344	0.044
14	Portugal	0.330	0.063
15	Italy	0.329	0.009
16	Finland	0.315	0.040
17	Latvia	0.297	0.059
18	Bulgaria	0.274	0.010
19	Sweden	0.266	0.039
20	Czechia	0.264	0.066
21	Greece	0.259	−0.054
22	Hungary	0.241	0.007
23	Slovenia	0.228	0.016
24	Luxembourg	0.172	0.039
25	United Kingdom	0.172	0.030
26	Romania	0.144	−0.132
27	Slovakia	0.109	0.020
28	Malta	0.104	0.050

are much greater. Germany shows the most significant growth, allowing it to exceed the European average, along with four other countries (Cyprus, Estonia, Croatia and Poland). The opposite is true for Italy and Greece. In addition, the critical situation that remains for the four countries defined in the version of the SEIB for all sectors, to which Romania is added, should be highlighted (figure 2).

3.3. A decomposition analysis of SEIB

The third step is to break down the analysis according to parameters and sectors in order to understand which has the greatest influence on final results. The analysis is carried out only for the SEIB for all sectors, since obviously the conclusions are specular for the other SEIB version.

3.3.1. A decomposition analysis of SEIB referred to parameters

The decomposition analysis referred to parameters is proposed in figure 3. The weight of turnover and value added is more significant than that of workers (table 3), making the value of the SEIB associated with the two economic parameters very significant in most of the countries analyzed. The combined sum of turnover and value added in terms of SEIB is 87%, 89% and 93% for Ireland, Denmark and the Netherlands, respectively. On the other hand, this percentage is less than half in Latvia (49%) and Croatia (46%), but above all Romania (31%) and Bulgaria (20%) underperform with respect to the rest of EU-28 countries.

3.3.2. A decomposition analysis of SEIB referred to sectors

The decomposition analysis referred to sectors is proposed in figure 4. The percentage weight of sectors $K = 1$ (Agriculture) and $K = 4$ (Manufacture of food, beverages and tobacco) is very important in the mix of all sectors (table 4) and, consequently, the leading countries in these sectors will have excellent performance at SEIB level. In fact, in 22 of the 28 countries examined, the most significant value is the SEIB associated with $K = 4$. Exceptions are Bulgaria, Greece, Hungary, Latvia, Romania and Slovenia, where $K = 1$ prevails; while the difference is minimal in Italy, Lithuania, Portugal and Spain.

Analyzing $K = 1$, it emerges that Romania is the leader with 0.216, followed by Greece 0.184 and Netherlands 0.180. Important performances are also seen

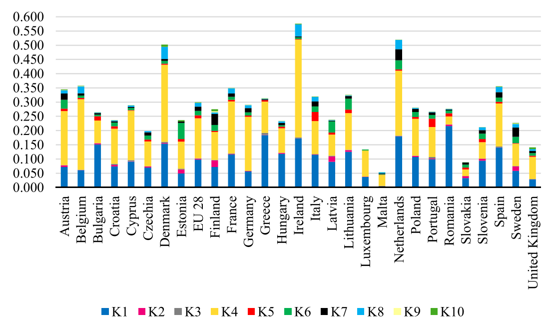

Figure 4. A decomposition analysis of SEIB for all sectors in 2019 as a function of bio-based sectors.

Table 7. SEIB values in 2019 considering an equal weight among the parameters.

SEIB for all sectors		SEIB for manufacturing and bio-energy sectors	
Country	Value	Country	Value
Ireland	0.566	Ireland	0.660
Netherlands	0.503	Denmark	0.569
Denmark	0.490	Netherlands	0.506
Belgium	0.351	Belgium	0.482
Spain	0.348	Austria	0.476
Austria	0.343	Lithuania	0.448
France	0.342	Germany	0.434
Lithuania	0.330	Cyprus	0.421
Greece	0.318	France	0.389
Italy	0.313	Estonia	0.366
Romania	0.299	Croatia	0.362
EU 28	0.297	Spain	0.354
Cyprus	0.289	Poland	0.352
Germany	0.289	Portugal	0.335
Poland	0.287	EU 28	0.327
Bulgaria	0.284	Italy	0.324
Portugal	0.273	Finland	0.314
Finland	0.271	Latvia	0.306
Latvia	0.243	Bulgaria	0.284
Croatia	0.241	Czechia	0.270
Estonia	0.238	Sweden	0.266
Hungary	0.235	Greece	0.264
Sweden	0.223	Hungary	0.250
Slovenia	0.216	Slovenia	0.234
Czechia	0.199	Luxembourg	0.173
United Kingdom	0.138	United Kingdom	0.168
Luxembourg	0.131	Romania	0.149
Slovakia	0.091	Slovakia	0.113
Malta	0.054	Malta	0.106

for Ireland 0.172, Denmark 0.154, Bulgaria 0.151 and Spain 0.140. As far as $K = 4$ is concerned, Ireland is the leader with a value of 0.344, followed by Denmark 0.271, Belgium 0.248 and Netherlands 0.229. Important values are also found for Germany 0.190, France 0.183, Cyprus 0.174 and Spain 0.151. From these results it emerges that the Manufacture of food, beverages and tobacco determines the first three positions in the overall ranking, however it is worth highlighting how the less significant performance of the Netherlands in this sector compared to Ireland and Denmark is then compensated for by that in $K = 1$. If Greece manages—thanks to 0.11 in $K = 4$—to be above the European average, the same does not happen for Romania. We then have Belgium and France which benefit from the $K = 4$ performance, while Spain has similar values for the two sectors mentioned above. The significant difference between the two sectors also explains why Belgium, along with Germany and Cyprus, has the most significant variation in the SEIB for manufacturing and bio-energy sectors.

As far as the other sectors are concerned, the most significant values are as follows: (a) $K = 5$ (Manufacture of bio-based textiles) with Italy 0.032 and Portugal 0.029; (b) $K = 6$ (Manufacture of wood products and furniture) with Estonia 0.057 followed by Latvia and Lithuania with 0.039; (c) $K = 7$ (Manufacture of paper) Finland and Netherlands with 0.039 and (d) $K = 8$ (Manufacture of chemicals, pharmaceuticals, plastics and bio-based rubber) Ireland 0.042 followed by Netherlands 0.033.

3.4. The assessment of the SEIB for all sectors—alternative scenario

The fourth step of the analysis is to calculate how the SEIB varies under alternative scenarios, which are obtained by varying the value of its variables. The first is that relating to the weight of socio-economic parameters (table 7). As far as SEIB for all sectors is concerned, the main change concerns Romania, which joins the other ten countries above the European average. In fact, it presents the most significant growth with 0.022, followed by Bulgaria with 0.020. The three leading countries, on the other hand, show the most significant decrease: Netherlands −0.017, Denmark −0.012 and Ireland −0.010. However, they remain at the top three positions of the ranking. As far as the SEIB for manufacturing and bio-energy sectors is concerned, it is Portugal that exceeds the European average. The most significant increases were recorded for Lithuania and Croatia. It is confirmed that Ireland and Denmark maintain the top two positions.

3.5. The socio-economic time performance of European countries based on SEIB

A further alternative analysis is one in which the parameter values for each sector have changed and consequently the weights among sectors also vary. Values that change over time can be considered, and in accordance with the previous section, 2017 values are calculated from scratch by applying an analysis of values at the macro sector level. The delta proposed in table 8 if negative indicates that 2019 performance is worse than 2017 performance. Specifically, the most significant reduction is associated with Slovakia due primarily to the reduction in the $K = 1$ sector (−0.014) and the leading country (Ireland) due primarily to the reduction in the $K = 8$ sector (−0.020). Lower-performing results are also

Table 8. SEIB for all sectors in 2017. The delta measures the difference between SEIB values in 2019 and 2017.

Ranking	Country	Value	Delta
1	Ireland	0.604	−0.028
2	Denmark	0.443	0.060
3	Netherlands	0.383	0.136
4	Austria	0.309	0.036
5	Lithuania	0.295	0.031
6	Belgium	0.284	0.074
7	France	0.281	0.069
8	Spain	0.279	0.077
9	Romania	0.275	0.002
10	Finland	0.273	0.002
11	Greece	0.255	0.058
12	Italy	0.254	0.067
	EU 28	0.244	0.056
13	Portugal	0.243	0.024
14	Estonia	0.242	−0.005
15	Cyprus	0.237	0.051
16	Croatia	0.233	0.004
17	Poland	0.227	0.054
18	Latvia	0.227	0.011
19	Germany	0.216	0.075
20	Hungary	0.210	0.023
21	Bulgaria	0.198	0.067
22	Sweden	0.182	0.045
23	Czechia	0.178	0.020
24	Slovenia	0.161	0.051
25	Luxembourg	0.140	−0.006
26	United Kingdom	0.130	0.011
27	Slovakia	0.119	−0.030
28	Malta	0.045	0.009

associated with Luxembourg and Estonia. By contrast, the most significant growth is for the second-ranked country overall (Netherlands) for increases in several sectors ($K = 1$, $K = 4$, $K = 6$, $K = 7$ and $K = 8$). Spain, Germany and Belgium show significant increases linked mainly to performance associated with $K = 4$.

This last step analysis has shown that the choice of values applied to macro sectors compared to micro sectors quantifies more accurately the actual socio-economic dimension of the bioeconomy and, also, the ranking of countries can vary significantly.

3.6. A comparison among bioeconomy indicators

Finally, the last stage of the analysis involves a comparison of the different indicators. In the absence of SEIB, indicators measuring turnover versus workers and value added versus workers could be used (Ronzon *et al* 2017, Ronzon and M'Barek 2018)—figure 5.

An increase in workers has a positive effect on the value of SEIB, while resulting in a decrease in both ratios turnover/workers and value added/workers. It is worth noting that the primary sectors ($K = 1$, $K = 2$ and $K = 3$) have lower values in turnover/workers. The $K = 10$ (Production of bio-electricity) has the highest value followed by $K = 9$ (Manufacture of liquid biofuels) with 1031 and 537 thousand € per

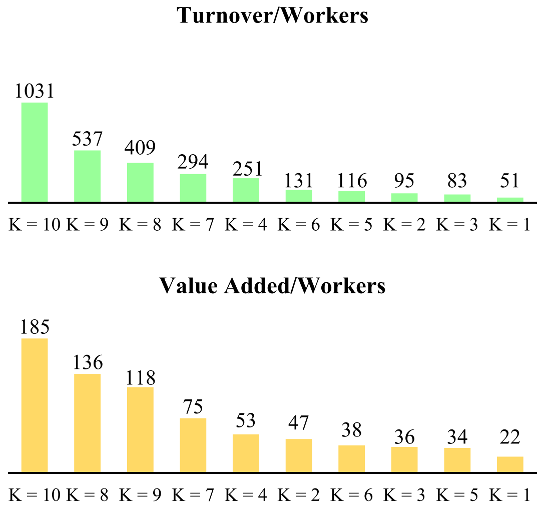

Figure 5. Ratio between turnover and workers and ratio between value added and workers in function of sectors. Both are expressed as thousand € per number of persons employed. Adapted by (European Commission 2019).

number of persons employed, respectively (figure 1). The ranking of sectors changes when we consider value added/workers where $K = 1$ remains the lowest but the other two primary sectors do not occupy the last positions. $K = 10$ still leads the field, followed this time by $K = 8$ (Manufacture of bio-based chemicals, pharmaceuticals, plastics and rubber (excluding biofuels)) with 185 and 136 thousand € per number of persons employed, respectively.

The next objective is then to compare the ranking of these two indicators with the SEIB (table 9), in which we show that increasing workers can only improve a sustainable performance. Within the SEIB, increasing this parameter acts in this direction. The results show changes. The performances of the first three countries are still significant, but it is Belgium that prevails with 407 and 106 thousand € per worker in terms of turnover and value added, respectively. Growth is also evident in Sweden and Finland, while among the countries occupying the last positions, United Kingdom and Luxembourg present a value above the European average in these indicators.

4. Discussion

Globalization has led to the idea of selling one's products all over the world and production has sometimes been concentrated where costs were lower. However, long supply chain models can feel geopolitical risks, and in addition, climate change leads to abrupt changes that can put the production chain at risk (Fernández-Miguel *et al* 2022). Lack of materials and components can cause production stoppages, leading to socio-economic damage.

The use of short and integrated supply chains and of bio-based resources produce not only environmental advantages but also social ones, since they

Table 9. A comparison of bioeconomy indicators in 2019. SEIB is dimensionless, while both turnover/workers and value added/workers are proposed as thousand € per worker.

SEIB		Turnover/workers		Value added/workers	
Ireland	0.576	Belgium	407	Belgium	106
Netherlands	0.520	Ireland	338	Denmark	98
Denmark	0.503	Denmark	335	Ireland	94
Belgium	0.358	Netherlands	328	Sweden	86
Spain	0.356	Sweden	290	Netherlands	81
France	0.350	Finland	288	Finland	80
Austria	0.345	France	223	France	60
Lithuania	0.326	Austria	207	Austria	59
Italy	0.320	Germany	207	Germany	58
Greece	0.313	United Kingdom	206	United Kingdom	58
EU 28	0.300	Italy	168	Italy	50
Germany	0.291	Spain	164	Spain	48
Cyprus	0.288	Luxembourg	159	Luxembourg	47
Poland	0.281	EU 28	138	EU 28	39
Romania	0.277	Estonia	123	Malta	33
Finland	0.275	Malta	111	Estonia	31
Portugal	0.267	Czechia	99	Cyprus	30
Bulgaria	0.264	Cyprus	88	Czechia	28
Latvia	0.238	Hungary	85	Hungary	26
Estonia	0.237	Slovakia	79	Slovenia	23
Croatia	0.236	Slovenia	73	Slovakia	21
Hungary	0.234	Lithuania	67	Latvia	20
Sweden	0.227	Portugal	65	Lithuania	20
Slovenia	0.212	Latvia	65	Croatia	19
Czechia	0.198	Poland	62	Portugal	19
United Kingdom	0.141	Croatia	56	Greece	17
Luxembourg	0.134	Greece	51	Poland	15
Slovakia	0.089	Bulgaria	19	Romania	6
Malta	0.054	Romania	19	Bulgaria	6

generate job opportunities and allow consumers to choose sustainable products (Vivien *et al* 2019, Ladu and Morone 2021). By promoting the uptake of a circular bioeconomy a growing demand for new highly skilled jobs will arise in several sectors such as agricultural, forestry, fisheries, aquaculture, marine as well as in the food, bioengineering and other bio-based sectors. This will call for the supply of new skills and training and education models, to march the growing and changing demand (European Commission 2022a). Indeed, the bioeconomy can redefine some business models, the ways in which stakeholders talk to each other, and if companies collaborate with each other, models of industrial symbiosis are identified that lead to the circular bioeconomy (Kardung and Drabik 2021, D'Adamo and Sassanelli 2022). However, such a transformation may require higher costs associated with the transition, which is why supportive policies that are implemented by different European countries are necessary.

The results of this work highlight that from the socio-economic parameters (turnover, value added and workers) it is necessary to identify indicators that monitor the progress of the bioeconomy (Ronzon *et al* 2020, 2022). The SEIB provides a snapshot of the health of the bioeconomy (D'Adamo *et al* 2020).

SEIB in 2019 shows signs of growth compared to 2017 data, and there are three countries (Ireland, Denmark and Netherlands) that show very encouraging results in the updated ranking. Probably the bioeconomy policies implemented among the first in Europe in these countries have pushed this phenomenon, but the same has not happened for example in Germany and Czechia. It should therefore be emphasized that national strategies are important but not sufficient for effective development. The key to these countries' success lies in the use of the resources they had and having made investments that yielded their benefits in terms of both turnover and value added. In addition, these countries also gave attention to the socio-economic parameter of the workers. If one looks at a framework based solely on the turnover/workers and value added/workers indicators (Ronzon and M'Barek 2018), it emerges that Belgium occupies the first position, while in SEIB there is a different situation. SEIB is able to enhance the role of workers, although it is regarded as the least relevant parameter. Some countries still make much use of the primary sector-based economy on which, however, further observations need to be made. It is worth highlighting how, in terms of added value per worker, their results do not occupy the last positions in the ranking and how the potential of agriculture is underestimated. In fact, it is not only basic for food safety (Wydra 2020), but also for the quality of products that affect human health. Moreover, it can be an element of attractiveness for some territories that combine the mix between industry and tourism activities. Additionally, there is a growing consensus 'that there are significant opportunities for employment growth as a result of regulatory change, the availability of new technologies which affect production processes, the capacity to develop new products […] and consumer preferences' (European Commission 2022a). Examples of areas of expansion would include novel foods, packaging, bio preservation, sensing and biosensors.

Bio-electricity production ranks first among the macro sectors in terms of the turnover/workers and value added/workers indicators and thus emerges among the innovative sectors. However, SEIB gives a different indication as it assigns greater weight to those sectors that most absolutely influence the development of the bio-economy. Among these are two sectors that have a very dominant position: (a) agriculture and (b) manufacture of food, beverages and tobacco.

This work therefore allows us to identify some policy suggestions. The first is that it is essential to monitor the progress of the bioeconomy in different countries by identifying the areas in which some countries are emerging. European funds could be used in this direction to strengthen these realities, making them centers of excellence and to compete globally. The second concerns the rediscovery of primary sectors that too often are put on the back burner because they probably provide fewer economic opportunities. However, the employment leverage is exceptional. The third direction is toward innovation that leads not only to reengineering processes but to bringing bio-based products into the production cycle in order to make the production process more environmentally friendly. This goal requires investing in the use of local resources and fostering industrial symbiosis among the different actors in the production chain. The fourth direction involves consumers, for whom the degree of knowledge toward bio-based products should be strengthened by also assessing their willingness to pay extra for such products. The introduction of incentives is desirable in this regard. The fifth direction is to encourage the development of active youth entrepreneurial activities by using European funds directly related to these issues, fostering collaboration and information programs. The sixth direction is to target the manufacturing and bio-energy sectors where it is necessary to push the sustainability-innovation combination by identifying business models that can intercept market needs. The quantitative approach of this work provides insights for which participatory models are needed that show the benefits of these inter-connected challenges.

5. Conclusions

This paper provides a socio-economic overview of the performance measurement of different bio-based sectors in Europe. The results show that three countries (Ireland, Denmark and Netherlands) present very positive performance. The opposite situation occurs for four countries (United Kingdom, Luxembourg, Slovakia and Malta).

The proposed approach is to harden the proposed framework on an indicator used in the literature, the SEIB, by identifying the following peculiarities: (a) the two versions of the SEIB allow to evaluate the incidence of primary sectors; (b) the decomposition analysis allows to evaluate how much the parameters and how much the single sectors affect the result; (c) alternative scenarios in which the values and the weights of the sectors and of the parameters are changed allow to give stability or not to the results obtained and (d) the comparison with classical indicators provide insights. This model can be replied for other geographical realities.

However, the work also has some limitations. First, it is an indicator of the bioeconomy that does not consider the environmental perspective, due to the lack of data, and thus does not assess how much different sectors can actually counteract climate change. The second critical aspect concerns the availability of data, which is restricted and sometimes outdated. Therefore, there is a need to call for projects that are directed in this direction.

The bioeconomy can provide support for sustainable development, monitoring of socioeconomic performance is useful for all stakeholders, and new interventions, including policy, are needed. However, change is first and foremost social, changing production and consumption patterns. It requires interconnected challenges and it puts us at a crossroads: to condemn future generations to obscurity or light.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

Antanasijević D, Pocajt V, Ristić M and Perić-Grujić A 2017 A differential multi-criteria analysis for the assessment of

sustainability performance of European countries: beyond country ranking *J. Clean. Prod.* **165** 213–20
Asada R and Stern T 2018 Competitive bioeconomy? Comparing bio-based and non-bio-based primary sectors of the world *Ecol. Econ.* **149** 120–8
Barbier E B and Burgess J C 2019 Sustainable development goal indicators: analyzing trade-offs and complementarities *World Dev.* **122** 295–305
Befort N 2020 Going beyond definitions to understand tensions within the bioeconomy: the contribution of sociotechnical regimes to contested fields *Technol. Forecast. Soc. Change* **153** 119923
Brizga J, Miceikienė A and Liobikienė G 2019 Environmental aspects of the implementation of bioeconomy in the Baltic sea region: an input-output approach *J. Clean. Prod.* **240** 118238
Bruckner M, Häyhä T, Giljum S, Maus V, Fischer G, Tramberend S and Börner J 2019 Quantifying the global cropland footprint of the European Union's non-food bioeconomy *Environ. Res. Lett.* **14** 045011
Cabernard L, Pfister S and Hellweg S 2022 Improved sustainability assessment of the G20's supply chains of materials, fuels, and food *Environ. Res. Lett.* **17** 034027
Calicioglu Ö and Bogdanski A 2021 Linking the bioeconomy to the 2030 sustainable development agenda: can SDG indicators be used to monitor progress towards a sustainable bioeconomy? *New Biotechnol.* **61** 40–49
Capasso M and Klitkou A 2020 Socioeconomic indicators to monitor Norway's bioeconomy in transition *Sustainability* **12** 3173
D'Adamo I, Falcone P M, Imbert E and Morone P 2022a Exploring regional transitions to the bioeconomy using a socio-economic indicator: the case of Italy *Econ. Politica* **39** 989–1021
D'Adamo I, Falcone P M and Morone P 2020 A new socio-economic indicator to measure the performance of bioeconomy sectors in Europe *Ecol. Econ.* **176** 106724
D'Adamo I, Gastaldi M, Imbriani C and Morone P 2021 Assessing regional performance for the sustainable development goals in Italy *Sci. Rep.* **11** 24117
D'Adamo I, Gastaldi M, Morone P, Rosa P, Sassanelli C, Settembre-blundo D and Shen Y 2022b Bioeconomy of sustainability: drivers, opportunities and policy implications *Sustainability* **14** 1–7
D'Adamo I and Sassanelli C 2022 Biomethane community: a research agenda towards sustainability *Sustainability* **14** 4735
Dima A M, Tantau A and Maassen M A 2022 Models for analysing the dependencies between indicators for bioeconomy in the European Union *Econ. Res. Istraživanja* **35** 1–18
Egenolf V and Bringezu S 2019 Conceptualization of an indicator system for assessing the sustainability of the bioeconomy *Sustainability* **11** 443
European Commission 2018 A new bioeconomy strategy for a sustainable Europe (available at: https://ec.europa.eu/info/research-and-innovation/research-area/environment/bioeconomy/bioeconomy-strategy_en)
European Commission 2019 JRC-Bioeconomics dataset (available at: https://datam.jrc.ec.europa.eu/datam/public/pages/previousFilters.xhtml?dataset=7d7d5481-2d02-4b36-8e79-697b04fa4278)
European Commission 2022a Promoting education, training and skills across the bioeconomy *Final Report* (Luxembourg: Publications Office of the European Union)
European Commission 2022b What is the bioeconomy (available at: https://ec.europa.eu/research/bioeconomy/policy/bioeconomy_en.htm)
Eversberg D and Fritz M 2022 Bioeconomy as a societal transformation: mentalities, conflicts and social practices *Sustain. Prod. Consum.* **30** 973–87
Fernández-Miguel A, Riccardi M P, Veglio V, García-Muiña F E, Fernández Del Hoyo A P and Settembre-Blundo D 2022 Disruption in resource-intensive supply chains: reshoring and nearshoring as strategies to enable them to become more resilient and sustainable *Sustainability* **14** 10909
Galanakis C M, Brunori G, Chiaramonti D, Matthews R, Panoutsou C and Fritsche U R 2022 Bioeconomy and green recovery in a post-COVID-19 era *Sci. Total Environ.* **808** 152180
Gawel E, Pannicke N and Hagemann N 2019 A path transition towards a bioeconomy-The crucial role of sustainability *Sustainability* **11** 3005
Heimann T 2019 Bioeconomy and SDGs: does the bioeconomy support the achievement of the SDGs? *Earths Future* **7** 43–57
Hurmekoski E, Smyth C E, Stern T, Verkerk P J and Asada R 2021 Substitution impacts of wood use at the market level: a systematic review *Environ. Res. Lett.* **16** 123004
Jander W 2022 Advancing bioeconomy monitorings: a case for considering bioplastics *Sustain. Prod. Consum.* **30** 255–68
Jander W, Wydra S, Wackerbauer J, Grundmann P and Piotrowski S 2020 Monitoring bioeconomy transitions with economic-environmental and innovation indicators: addressing data gaps in the short term *Sustainability* **12** 4683
Jarosch L, Zeug W, Bezama A, Finkbeiner M and Thrän D 2020 A regional socio-economic life cycle assessment of a bioeconomy value chain *Sustainability* **12** 1259
Kardung M *et al* 2021 Development of the circular bioeconomy: drivers and indicators *Sustainability* **13** 413
Kardung M and Drabik D 2021 Full speed ahead or floating around? Dynamics of selected circular bioeconomies in Europe *Ecol. Econ.* **188** 107146
Kumar A, Sah B, Singh A R, Deng Y, He X, Kumar P and Bansal R C 2017 A review of multi criteria decision making (MCDM) towards sustainable renewable energy development *Renew. Sustain. Energy Rev.* **69** 596–609
Ladu L and Morone P 2021 Holistic approach in the evaluation of the sustainability of bio-based products: an integrated assessment tool *Sustain. Prod. Consum.* **28** 911–24e6
Maksymiv Y, Yakubiv V, Pylypiv N, Hryhoruk I, Piatnychuk I and Popadynets N 2021 Strategic challenges for sustainable governance of the bioeconomy: preventing conflict between SDGs *Sustainability* **13** 8308
O'Brien M, Wechsler D, Bringezu S and Schaldach R 2017 Toward a systemic monitoring of the European bioeconomy: gaps, needs and the integration of sustainability indicators and targets for global land use *Land Use Policy* **66** 162–71
Ols C and Bontemps J-D 2021 Pure and even-aged forestry of fast-growing conifers under climate change: on the need for a silvicultural paradigm shift *Environ. Res. Lett.* **16** 24030
Ronzon T, Iost S and Philippidis G 2022 Has the European Union entered a bioeconomy transition? Combining an output-based approach with a shift-share analysis *Environ. Dev. Sustain.* **24** 8195–217
Ronzon T and M'Barek R 2018 Socioeconomic indicators to monitor the EU's bioeconomy in transition *Sustainability* **10** 1745
Ronzon T, Piotrowski S, M'Barek R and Carus M 2017 A systematic approach to understanding and quantifying the EU's bioeconomy *Bio-based Appl. Econ.* **6** 1–17
Ronzon T, Piotrowski S, Tamosiunas S, Dammer L, Carus M and M'barek R 2020 Developments of economic growth and employment in bioeconomy sectors across the EU *Sustain* **12** 4507
Sanz-Hernández A, Esteban E and Garrido P 2019 Transition to a bioeconomy: perspectives from social sciences *J. Clean. Prod.* **224** 107–19
Shuai C, Yu L, Chen X, Zhao B, Qu S, Zhu J, Liu J, Miller S A and Xu M 2021 Principal indicators to monitor sustainable development goals *Environ. Res. Lett.* **16** 124015
Su W, Zhang D, Zhang C and Streimikiene D 2020 Sustainability assessment of energy sector development in China and European Union *Sustain. Dev.* **28** 1063–76
Szopik-Depczyńska K, Cheba K, Bąk I, Stajniak M, Simboli A and Ioppolo G 2018 The study of relationship in a hierarchical structure of EU sustainable development indicators *Ecol. Indic.* **90** 120–31

Vavrek R and Chovancová J 2019 Assessment of economic and environmental energy performance of EU countries using CV-TOPSIS technique *Ecol. Indic.* **106** 105519

Vivien F-D, Nieddu M, Befort N, Debref R and Giampietro M 2019 The hijacking of the bioeconomy *Ecol. Econ.* **159** 189–97

Wydra S 2020 Measuring innovation in the bioeconomy—Conceptual discussion and empirical experiences *Technol. Soc.* **61** 101242

Xu M *et al* 2021 US–China collaboration is vital to global plans for a healthy environment and sustainable development *Environ. Sci. Technol.* **55** 9622–6