

1 Article

## 2 **Assessing the contribution of bioeconomy to the total** 3 **economy: a review of national frameworks**

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11 **Abstract:** Developments in technology have enabled envisioning the derivation of materials and  
12 products from renewable biomass, as an alternative to finite fossil-based resource consumption.  
13 Therefore, bioeconomy is regarded as an opportunity for sustainable economic growth. Countries  
14 are formulating strategies in accordance with their goals to attain from bioeconomy. Proper  
15 measurement, monitoring and reporting of the outcomes of these strategies is crucial for long-term  
16 success. This study aims to critically evaluate the national methods used for the measurement,  
17 monitoring and reporting of bioeconomy contribution to the total economy. For this purpose,  
18 research and surveys have been conducted on selected countries (Argentina, Germany, Malaysia,  
19 the Netherlands, South Africa and the United States). The results reveal that the bioeconomy targets  
20 set up in the strategies often reflect country's priorities and comparative advantages. However,  
21 comprehensive approaches to measure and monitor bioeconomy progress are frequently lacking.  
22 Most countries only measure the contribution to gross domestic product (GDP), turnover and  
23 employment of the sectors included in their bioeconomy definition, which may provide an  
24 incomplete picture. In addition, this study identifies the mismatch between the targets and  
25 measurement methods, as the environmental and social impacts of bioeconomy are often foreseen,  
26 but not measured. It is concluded that existing global efforts towards a sustainable bioeconomy  
27 monitoring can be strengthened and leveraged to measure progress towards sustainable goals.

28 **Keywords:** Bioeconomy; Bio-based products; GDP; Policy measures; Sustainability assessment;  
29 Sustainable development

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### 31 **1. Introduction and background**

32 Modern economies rely on resources which are finite in nature. On top of their long-term  
33 unsustainability, utilization of fossil fuel resources and unsustainable consumption of derived  
34 products also pose risk to societies and the environment due to their negative impacts such as climate  
35 change and ecosystem degradation [1,2]. Nevertheless, advancements in industrial biotechnology  
36 have enabled derivation of materials, chemicals and energy from renewable biomass, which could  
37 provide substitutes over fossil-based and finite resources [3]. This substitution potential forms the  
38 core of a still-evolving bioeconomy concept.

39 The literature on bioeconomy vision has been evolving in parallel to the concept, and has been  
40 clustered under three major perspectives: (1) the biotechnology vision which emphasizes innovations  
41 and utilization of biotechnology at commercial scales; (2) the bioresource vision emphasizes the  
42 improvement of value chains on upstream biomass production; (3) the bioecology vision which  
43 emphasizes the positive impacts of energy and resource optimization on ecosystem health [4]. These  
44 perspectives underline the potential of bioeconomy in the opportunities it offers, such as low-carbon

45 economic growth, preservation of natural resources, restoration of environmental and ecosystem  
46 health, and welfare of rural communities.

47 Due to its promising potential in addressing these global challenges, bioeconomy has been  
48 directly or indirectly included in the policy agendas worldwide [5,6]. Country objectives and  
49 bioeconomy priorities encompass economic growth, employment, energy security, food security,  
50 fossil fuel reduction, mitigation and adaptation to climate change, and rural development [7]. With  
51 respect to their potentials in deploying the bioeconomy vision, countries have different opportunities,  
52 which might also affect their policies. Countries can be classified as countries with (1) an abundance  
53 of renewable biological resources, but a lack of downstream processing industries, (2) both high  
54 feedstock potential and advanced processing industries, and (3) low feedstock potential but  
55 advanced processing industries [8]. These variations in the potential also create differences in  
56 countries' objectives for adopting a bioeconomy strategy and in the evaluation of success towards  
57 their achievement.

58 Measuring bioeconomy contribution to countries' overall economy can be an important  
59 indicator of development. No internationally agreed methodology exists today to measure progress  
60 in attaining the ambitions and targets set by bioeconomy policies and strategies. Moreover, given the  
61 differences between countries' constraints, opportunities and priorities, the development of a  
62 uniform way to assess the contribution of bioeconomy to the national economy is challenging. This  
63 lack of a coherent methodology could create confusion when trying to compare the importance of  
64 bioeconomy within and across countries. One first step towards a globally recognized methodology  
65 could be to assess the current efforts of individual countries to define bioeconomy, and the  
66 frameworks for measuring, monitoring and reporting its contribution.

67 Typical economic models that can be adopted to measure the bioeconomy contribution to a  
68 country's economy include the value added/GDP approach; Input-Output (I-O) and Social  
69 Accounting Matrix (SAM) analysis; Computable General Equilibrium (CGE) Model; Partial  
70 Equilibrium (PE) Model and other economic models and tools [9]. However, these approaches do not  
71 systematically consider environmental and social aspects. In fact, the objective of this study is to  
72 analyse how the contribution of bioeconomy is measured in the overall national economy, using  
73 information from a geographically representative list of countries (Argentina, Germany, Malaysia,  
74 the Netherlands, South Africa and the United States). Furthermore, the alignment of the country  
75 objectives and the parameters measured have been analysed, in order to assess whether social and  
76 environmental impacts of bioeconomy were captured through selected measurement, monitoring  
77 and reporting frameworks adopted by the countries.

78 Within the scope of this study, the bioeconomy has been defined as "the knowledge-based  
79 production and utilization of biological resources, biological processes and principles to sustainably  
80 provide goods and services across all economic sectors" development [7]. It involves three elements:  
81 (1) The use of renewable biomass and efficient bioprocesses to achieve a sustainable production; (2)  
82 The use of enabling and converging technologies, including biotechnology; (3) Integration across  
83 applications such as agriculture, health and industry. In accordance with the Food and Agriculture  
84 Organization of the United Nations (FAO) development [7], the term "bio-based economy" excluded  
85 the food and feed production. Instead, it was used to take the production of non-food goods into  
86 consideration; i.e. bio-based materials, chemicals, and pharmaceuticals; pulp and paper; construction  
87 materials; textiles; and bioenergy. "Bio-based industry" refers to the industrial production of all  
88 possible bio-based goods. The strategies related to bioeconomy, bio-based economy and bio-  
89 industries were all considered as "bioeconomy strategies". This assessment has been built upon  
90 previous and ongoing efforts to foster global bioeconomy. In this respect, the countries to be  
91 investigated have been selected among the members of the FAO International Sustainable  
92 Bioeconomy Working Group (ISBWG), which includes 23 members as of March 2018: 11 countries  
93 (Argentina, Brazil, China, Germany, Italy, Kazakhstan, Malaysia, the Netherlands, South Africa,  
94 Uruguay and United States), the German Bioeconomy Council, the European Union (EU)  
95 Commission, Organisation for Economic Co-operation and Development (OECD), International  
96 Center for Tropical Agriculture (CIAT), Stockholm Environment Institute (SEI), United Nations

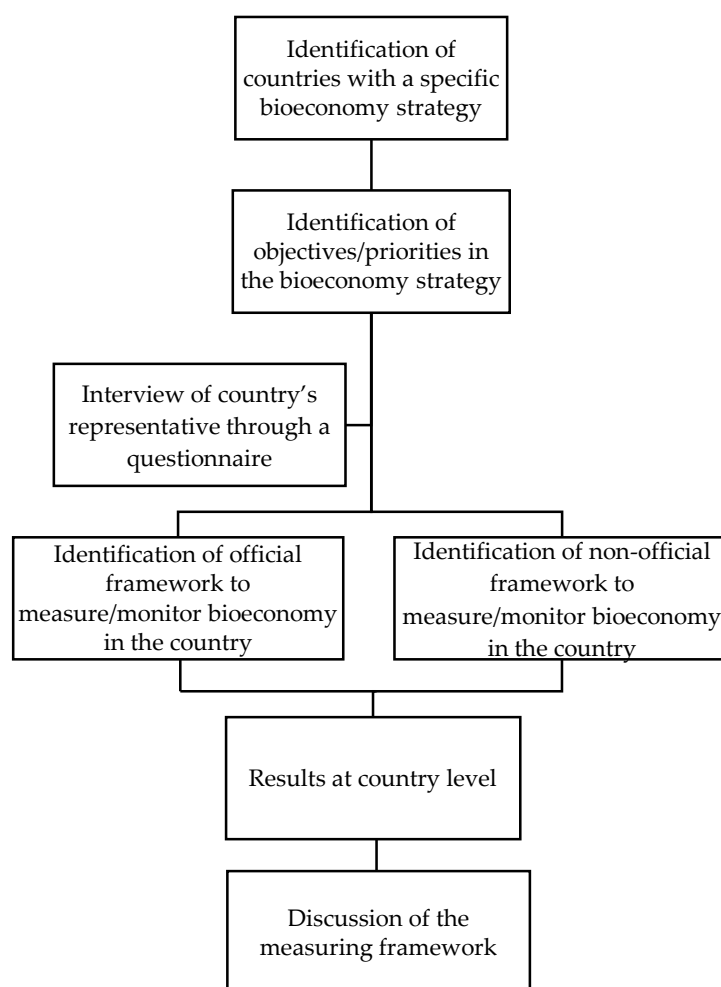
97 Environment Programme (UNEP), World Wide Fund (WWF), the Nordic Council of Ministries, the  
 98 EU Bio-Based Industries Consortium, Wageningen University, the World Business Council for  
 99 Development (WBCSD) and FAO.

100 The countries selected for the study are located in five continents, differ in terms of level of  
 101 economic development and have different bioeconomy strategies and priorities. For instance, some  
 102 countries have little land availability but advanced technologies, while others prioritize farmers and  
 103 rural development and have greater land availability. For all the countries, the study reviews  
 104 bioeconomy objectives and priorities as well as measurement, monitoring and reporting frameworks.  
 105 From the sample countries and a review of existing literature, a pathway towards a sustainable  
 106 bioeconomy monitoring is then proposed.

## 107 2. Approach and Methods

108 The study was based on desk research of policy documents, strategies and statements on the  
 109 bioeconomy and its measurement for a selected number of countries (Argentina, Germany, Malaysia,  
 110 the Netherlands, South Africa and the United States). Because of their demonstrated interest in  
 111 developing a global bioeconomy framework, the selection process was primarily performed among  
 112 the ISBWG member countries, following the selection process illustrated in Figure 1. The structural  
 113 organization of the analysis included an evaluation of the available information in terms of: (1) how  
 114 countries define bioeconomy; (2) which are the objectives and/or priorities of their strategy; (3) the  
 115 methodology they use to measure, monitor and report the contribution of bioeconomy to their  
 116 economy or objectives (**Figure 1.** ).

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**Figure 1.** Selection process and structural organization of the analysis

120 The relevant information for the analysis was gathered from official bioeconomy strategies and  
 121 documents, upon availability. When a government official document on how to measure the  
 122 contribution of bioeconomy to the total economy was not available, commissioned studies, studies  
 123 from research institutes and/or non-profit organizations were used instead. Table 1 summarizes the  
 124 sources of information and documents analysed in order to understand the definition of bioeconomy,  
 125 the objectives/priorities of the bioeconomy strategy, and the measurement, monitoring and reporting  
 126 frameworks established by each selected country. Whenever possible, the information was  
 127 complemented and validated by a survey, distributed to government representatives (Table 2). The  
 128 survey included the same questions to which answers were sought while scanning through the  
 129 written materials.

130 **Table 1.** Sources of information for the selected countries.

	<b>Bioeconomy definition and strategy</b>	<b>Objectives/ priorities of the strategy</b>	<b>Measurement, monitoring and reporting framework</b>
<b>Argentina</b>	Ministry of Agroindustry (MINAGRO) [10]	MINAGRO [10]	Bolsa de Cereales [11]
<b>Germany</b>	Federal Ministry of Food and Agriculture (BMEL), and the Federal Ministry for Education and Research (BMBF) [12]	National Policy Strategy on Bioeconomy [13]	A comprehensive and system monitoring approach to measure the contribution of German BE to the overall economy is currently under development
<b>Malaysia</b>	National Biotechnology Policy (NBP); the BioNexus Status (BNX); the Bioeconomy Transformation Programme (BTP); the Bioeconomy Community Development Programme (BCDP); National Biomass Strategy 2020 ("NBS 2020") [14]	BTP and BCDP [14]	MOSTI and Bioeconomy Corporation ([14], [15])
<b>The Netherlands</b>	Netherlands Enterprise Agency (RVO) [16]; CE Delft [17]; Agency Ministry of Economic Affairs (NOST) [18]; NNFCC [19]	NOST [18]; NNFCC [19]	Bio-based economy protocol monitor [16]; NOVA Institute [20]; CE Delft [17]; EC Bioeconomy Knowledge Centre [21]
<b>South Africa</b>	Public Understanding of Biotechnology [22]; National Biotechnology Strategy [23]	National Biotechnology Strategy [23]	National Biotechnology Strategy [23]; ongoing study to establish a framework to develop indicators to measure the growth of the BE in South Africa [24]
<b>USA</b>	National Bioeconomy Blueprint [25]; The Billion Ton Bioeconomy Vision [26]	National Bioeconomy Blueprint [25]; The Billion Ton Bioeconomy Vision [26]	USDA reports ( [27–29]); Department of Energy [30]

131 Information collected through desk research and surveys has been used for the analysis and has  
 132 been complemented with an extensive literature review of objectives and priorities of bioeconomy  
 133 strategies in other low, middle and high income countries (outside the study focus) in order to  
 134 improve the quality of the discussion. For this purpose, the survey was distributed to all ISBWG  
 135 members (not only to those in the study focus).

136 **Table 2.** Questionnaire submitted to ISBWG members on assessing bioeconomy contribution to  
 137 countries' economy

<b>Bioeconomy definition</b>
How does your Country define bioeconomy?
Which sectors are included into your bioeconomy strategy? (e.g. Agriculture; Automotive and mechanical engineering; Chemistry (incl. bioplastics); Biofuels/bioenergy; Biorefining; Construction/Building industry; Consumer goods such as cosmetics and cleaning products; Feed; Fisheries; Food and Beverage industry; Forestry; Health; Knowledge/Innovation; Mining; Pharmaceuticals industry; Pulp and paper; Textiles)
<b>Objectives/priorities</b>
Which are the objectives/priorities of your country strategy (e.g. food security, energy security, fossil fuel reduction, rural development, economic growth, employment, mitigation and adaptation to climate change, etc.)?
<b>Measurement, monitoring and reporting framework</b>
Does the country strategy include criteria to measure the contribution of bioeconomy to the overall economy? If yes, which ones?
Which approach does your country use to measure bioeconomy contribution? (e.g. GDP approach; Input-Output matrix; Computable General Equilibrium (CGE) Model; Partial Equilibrium (PE) Model)
Does your country measure the impact of bioeconomy on the following areas? (Turnover/sales; Value added; Job creation; Market development; Investments; Intellectual property; R&D spending; Trade balance; Poverty alleviation; Food security and sustainable agriculture; Health and well-being; Education; Gender equality; Availability and sustainable management of water; Access to affordable, reliable, sustainable and modern energy; Inclusive and sustainable industrialization and innovation; Inequality and inclusiveness; Inclusive, safe, resilient and sustainable cities; Ensure sustainable consumption and production patterns; Climate change; Oceans, seas and marine resources; Terrestrial ecosystems, forests, land degradation and biodiversity)
Are indicators to measure bioeconomy contribution defined? If so, which ones?
<b>Short discussion</b>
Which is, in our opinion, the main limitation of your country approach to measure bioeconomy contribution?

### 138 3. Analysis and Results

#### 139 3.1. Bioeconomy definitions and strategies

140 It is observed that the sectors and sub-sectors considered in 'bioeconomy' were different among the  
 141 analysed countries, which is a reflection of the differences in their priorities and strategies. Table 3  
 142 summarizes the various sectors included in the bioeconomy definition by the six analysed countries,  
 143 and the sectors taken into account for the quantification of bioeconomy contribution to overall  
 144 national economy. The first important point is the variation in the definition of bioeconomy. For  
 145 instance, the Netherlands has a focus on *bio-based economy*, excluding the agriculture and food sectors  
 146 [17] and still has not agreed on a which sectors are included in the bioeconomy [31]. The United States  
 147 aims to analyse the bioeconomy, but USDA shows results limited to *bio-based products industries*,  
 148 which exclude the energy, food, feed, livestock, and pharmaceutical industries.

149 According to Argentina, the bioeconomy includes agriculture, forestry, fishing, food production  
 150 and pulp and paper production, as well as parts of textile, chemical, energy and biotechnological

151 industries (medical and pharmaceutical industry). The German bioeconomy includes agriculture,  
 152 forestry, fishing, manufacturing and trading of bio-based products. Similarly, the Malaysian  
 153 bioeconomy includes agriculture, forestry, fisheries, food, feed, healthcare wellness products,  
 154 chemicals and renewable energy. South Africa's bioeconomy strategy focuses on agriculture,  
 155 industrial and environmental bio-innovation and health, but has yet to develop metrics to monitor  
 156 performance.

157 **Table 3.** Sectors included into BE strategy and monitoring in the selected countries

	Argentina	Germany	Malaysia	Netherlands*	South Africa	USA*
Agriculture	■ ■	■ ■	■ ■		■	■ ■
Automotive and mechanical engineering		■ ■				
Chemistry (incl. bioplastics)	■ ■	■ ■	■ ■	■ ■	■	■ ■
Biofuels/bioenergy	■ ■	■ ■	■ ■	■ ■	■	
Biorefining		■ ■	■ ■		■	■ ■
Construction/Building industry		■ ■				
Consumer goods (e.g. cosmetics, cleaners)	■ ■	■ ■			■	
Feed	■ ■	■ ■	■ ■		■	
Fisheries	■ ■	■ ■	■ ■		■	
Food and Beverage industry	■ ■	■ ■	■ ■		■	
Forestry	■ ■	■ ■	■ ■	■ ■**	■	■ ■
Health			■ ■		■	
Knowledge/Innovation		■ ■	■ ■	■ ■	■	
Mining					■	
Pharmaceutical industry	■ ■	■ ■	■ ■	■ ■	■	
Pulp and paper	■ ■	■ ■		■ ■	■	
Textiles	■ ■	■ ■		■ ■	■	■ ■
References:	[11]	[12]	[32]	[20]	[33,34]	[29]

158 \*The monitoring system analysis for the Netherlands refer to bio-based economy and the results for the US  
 159 refer to bio-based products industries. \*\* Only forest-based industry.

160 **Legend:** ■ - included in bioeconomy strategy, ■ ■ - included in the bioeconomy strategy and monitored or  
 161 measured.

162 It is worthwhile to note that the decision on which sectors to include is also relevant when trying  
 163 to measure the bioeconomy's contribution to countries' economies in terms of GDP and value added,  
 164 since the calculations would only take the included sectors into account [35].

### 165 3.2. Bioeconomy objectives and priorities

166 The sectors included in the bioeconomy strategy often reflect the priorities identified by the  
 167 country and comparative advantages linked for instance to endowment in biomass resources,  
 168 historical economic specialization, labour productivity and past investments in R&D [7,11,36–40].

169 For instance, in Argentina, bioeconomy is seen as a tool for sustainable development in the  
 170 country. It is recognized as a positive alternative for the generation of new behaviours and sources  
 171 of employment to face the double challenge of climate change and the continued need for economic  
 172 progress indispensable for poverty reduction [10].

173 In Germany, the National Policy Strategy on Bioeconomy's priorities for advancing towards a  
 174 knowledge-based bioeconomy are: the development of a secure supply of high-quality food; the  
 175 transition from a fossil-based economy to an economy that is increasingly efficient in terms of raw  
 176 materials and based on renewable resources; the supply of renewable resources; the sustainable use  
 177 of renewable resources while conserving biodiversity and soil fertility; protection of the climate;  
 178 strengthening of Germany's innovative power and its international competitiveness in business and  
 179 research; securing and creating employment and added value, particularly in rural areas; and  
 180 sustainable consumption [13].

181 In Malaysia, bioeconomy is seen as a key contributor to economic growth, which can provide  
 182 benefits to the society via breakthroughs in agricultural productivity, innovations in healthcare and  
 183 the adoption of sustainable industrial processes [15].

184 The objectives of the South African bioeconomy strategy are to make the country more  
185 competitive internationally (especially in the industrial and agriculture sectors); to create more  
186 sustainable jobs; to enhance food security; and to create a greener economy as the country shifts  
187 towards a low-carbon economy [23]. In particular, the strategic economic sectors identified are i)  
188 agriculture, ii) health and iii) industry and environment.

189 In the Netherlands, the bioeconomy strategy encourages knowledge development and  
190 innovation in nine top sectors: agriculture and food, water, chemicals, energy, life sciences and health,  
191 horticulture and propagation materials (seed stock), logistics, high-tech systems and materials and  
192 creative industries [18]. However, the Dutch government focuses more often on the bio-based  
193 economy, defined as “economic activity based on biomass, with the exception of human food and  
194 feed”, with the condition that it is based on recently captured carbon [41]. The most important drivers  
195 behind the adoption of a bio-based economy strategy were: striving for more sustainability (reduction  
196 of CO<sub>2</sub> emissions, circular economy); the awareness of the finite nature of fossil fuels, and the  
197 economic opportunities offered to Dutch businesses through the use of renewable biological  
198 resources and residues [18].

199 In the USA, the five strategic objectives introduced by the National Bioeconomy Blueprint aimed  
200 to generate economic growth and address societal needs. Some of these strategies include supporting  
201 R&D investments, facilitating the transition of bio-inventions from research lab to market, developing  
202 and reforming regulations, updating training programmes, and aligning academic institution  
203 incentives with student training for national workforce needs. They also include identifying and  
204 supporting opportunities for the development of public-private partnerships and precompetitive  
205 collaborations in their objectives [25].

### 206 3.3. Measurement, monitoring and reporting frameworks

207 The countries selected for the study use various approaches for measuring bioeconomy  
208 contribution to their economy and in attaining the objectives.

209 In the case of Argentina, a standard approach was adopted to measure the contributions (gross  
210 production value and value added) of bio-based products to the national GDP, referencing the  
211 general principles of the System of National Accounts (SNA) for the calculation of GDP and  
212 internationally comparable satellite accounts (e.g. for education, capital, productivity and  
213 environment). A paper by the an intermediate service provider *Bolsa de Cereales* [11] designs a general  
214 methodology for the criteria, procedures, and database to be used in the measurement of bioeconomy  
215 and its contribution to GDP. The sectors included in the calculation of the bioeconomy’s contribution  
216 to the GDP are: “agriculture, forestry, fishing, food production and pulp and paper production, as  
217 well as [bio-based] fractions of textile and chemical industry, and energy and biotechnological  
218 industries (health and pharmaceutical industry)” [11], in alignment with the sector included in the  
219 country’s bioeconomy strategy.

220 In Germany, most of the areas contributing to bioeconomy are monitored by traditional  
221 statistical accounts [12]. However, in most of the cases, methodologies for data collection and  
222 assessment are not streamlined to assess the impact of the bioeconomy. This leads to sparse  
223 information on impacts, along with data gaps, uncertainties, lack of comparability of results and  
224 potentially double-counting of impacts. A comprehensive and system monitoring approach to  
225 measure the contribution of German bioeconomy to the overall economy is currently under  
226 development by a joint inter-ministerial undertaking, made of three main projects: the monitoring of  
227 biomass flows, the Systemic Monitoring and Modelling of the Bioeconomy (SYMOBIO) and the  
228 identification of economic key performance indicators to monitor the bioeconomy [42].

229 Malaysia has developed a Bioeconomy Contribution Index (BCI) to measure the contribution of  
230 bioeconomy to the overall economy, which is a combination of five components/parameters:  
231 bioeconomy value-added, bio-based exports, bioeconomy investments, bioeconomy employment,  
232 and productivity performance [14]. The BCI is a comparative tool designed to provide a holistic view,  
233 encompassing multiple aspects of the bioeconomy, and it is used to identify trends, patterns and  
234 synergies within the industry. The index compares the performance of each specific component for a

235 selected year against the adjusted (i.e., accounting for changes in variables such as inflation rates,  
236 import-export values) expected base performance (in the base year 2005), determined by a Dynamic  
237 Computable General Equilibrium (DCGE) model [15]. The share of bioeconomy contribution to  
238 national development is estimated from the SAM, assuming that Malaysia is a price taker country  
239 [43].

240 Since the Netherlands lacks a clear protocol on defining the boundaries of the bioeconomy, until  
241 now their focus has been on the bio-based economy (BBE). In 2013, the Netherlands established a BBE  
242 monitoring protocol to quantify its size, and to monitor its development over time, in order to make  
243 trends visible, and comparable with developments abroad [16]. The protocol defines the system  
244 boundaries, the units to express the size of BBE, and utilization of available data or their collection, if  
245 missing. The protocol is built on existing statistical data on production and consumption, prevents  
246 double-counting of bio-based raw materials and accounts for raw material flows monitoring.  
247 However, it raises some problems linked to classification of business sectors, classification of product  
248 groups, and timely acquisition of data [16].

249 The South African bioeconomy strategy [23] contains some indicators to monitor progress in the  
250 bioeconomy in comparison with other high and middle-income countries, broadly divided into  
251 “knowledge and skills” indicators (full-time equivalent researchers, scientific publications,  
252 bioeconomy-related publications) and “financial support” indicators (gross domestic expenditure on  
253 R&D as percentage of GDP; funding and governmental support). Moreover, the methodology  
254 provides eighteen output indicators (related to industry; market; knowledge transmission and  
255 application; and knowledge base and human resources) to be used to track and monitor the  
256 bioeconomy strategy [23]. However, systematic metrics to measure and monitor South Africa’s  
257 bioeconomy have not yet been implemented. Ongoing efforts are anticipated to result in detailed  
258 implementation plans and value propositions for specific sectors and initiatives that will help refine  
259 targets [34].

260 The USDA report [29] examines and quantifies the effect of the bio-based products industry from  
261 an economics and jobs perspective at the state level. It was preceded by a report analysing the effect  
262 at national level [28] and by another report [44] which provides a snapshot of available information  
263 on the bioeconomy in the country and a platform upon which to build future efforts to measure the  
264 bioeconomy. The report adopts a three-pronged approach to gather information: interviews of  
265 representatives of government, industry, and trade associations involved in the bio-based products;  
266 data collection from government agencies and published literature on the bio-based products  
267 industry; and economic modelling. Despite being intended as a platform for understanding and  
268 tracking the progress of the bioeconomy in the United States, the USDA 2016 report does not provide  
269 a complete picture of the bioeconomy, as it does not report on the bioenergy sector, which is included  
270 in the U.S. strategy. Instead, it only focuses on seven major sectors chosen to represent the bio-based  
271 industry’s contribution to the US economy (agriculture and forestry; biorefining; bio-based  
272 chemicals; enzymes; bioplastic bottles and packaging; forest products and textiles). In 2017, also the  
273 Department of Energy (DOE) provided some figures about the size of the bioeconomy [30], building  
274 up the Billion Ton Bioeconomy Vision, but without a systematic measurement approach. The DOE  
275 estimates are taken from a paper considering direct employment and revenues from biomass  
276 resources fed into a number of end-uses and products including heat and power generation, bio-  
277 based chemicals and products (including wood pellets), and biofuels and coproducts [45].

### 278 3.4. Limitations in data availability and statistical approaches

279 Most of the analysed countries currently measure the contribution of bioeconomy to their GDP  
280 and other economic variables only. This economic approach, however, has some limitations to reflect  
281 the contribution in the economic sphere, above all because no standard methodology has been  
282 established to enable international comparison of bioeconomy contribution to GDP. Additionally, as  
283 mentioned above, products and activities comprised within the bioeconomy greatly vary according  
284 to country’s priorities and comparative advantages.



285 The most common classifiers of economic activity, trade and products at international-level  
286 (International Standard Industrial Classification (ISIC), North American Industry Classification  
287 System (NAICS), Classification of Economic Activities in the European Community (NACE),  
288 Nomenclature for External Trade (NET), and Classifier per Category (CPC)) are not compatible with  
289 the complexity of the bioeconomy [11,38] since they are not appropriate for the heterogeneous nature  
290 and variety of bio-based products. ISIC, NACE and NAICS group production units according to the  
291 similarity of their productive processes, technology, inputs and equipment. Their classification  
292 criteria make no distinction between bio or non-bio inputs [11]. Even the System of National Accounts  
293 (SNA 08) from the United Nations, which provides recommendations for measuring the national  
294 production, wellbeing and other economic issues in an internationally comparable way, does not  
295 allow to measure the bioeconomy [11]. Classifiers based on the traditional industrial activities are not  
296 compatible with the bio-based industry. This can lead to under or over-estimation of the size of the  
297 bioeconomy.

298 The high number of bio-based products and their heterogeneity make it very difficult to provide  
299 a full quantitative picture of the status and evolution of the bioeconomy [46]. Often, data on the  
300 bioeconomy are retrieved from surveys of the bio-based industry [11,27,47]. These surveys represent  
301 an important first step for a systematic approach to quantify the bioeconomy; however, they face  
302 difficulties in assembling the requested data and suffer from incomplete response rate [47]. These  
303 limitations are even more relevant in low and middle-income countries, where statistical systems are  
304 not well-developed. Under these circumstances, the surveys may not be updated and/or may include  
305 limited and biased samples (as shown for instance by the Argentinian and South Africa analyses,  
306 where the last company surveys were taken in 2003 [48]). Digitalization efforts as the ones undertaken  
307 in Malaysia to improve data collection can play an important role in the measurement and monitoring  
308 of bioeconomy.

#### 309 **4. Discussion**

##### 310 *4.1 The need for defining the bioeconomy boundaries at national, regional and global levels*

311 Due to the lack of a homogenous definition of bioeconomy and its sectors, a common ground  
312 which enables comparing the contribution of bioeconomy among countries is missing. Also at  
313 national level, the definition of the bioeconomy boundaries is sometimes unclear. For instance, in the  
314 case of the Netherlands, the estimated impacts of bioeconomy were different among the official  
315 studies analysed, due to the variety of methodologies and input data [17,20,21]. Also in the U.S., most  
316 of the sectors considered by the DOE to estimate the size of bioeconomy were excluded from the  
317 USDA 2016 report, leading to different estimates of the bioeconomy impacts in the country [29,30].  
318 For this reason, the efforts of the U.S. Biomass R&D Board to coordinate programmes within and  
319 among departments and agencies of the federal government towards a single, harmonized  
320 bioeconomy vision should ideally produce a single comprehensive approach able to monitor and  
321 measure all the sectors included in the vision in a coherent way.

322 When the countries do not have a holistic bioeconomy strategy, they tend to adopt a fragmented  
323 approach by separately considering the different uses of biomass in each sector (e.g. agriculture,  
324 forestry, energy, transport). This approach to governing the bioeconomy leads to different policies  
325 for different uses of biomass, different incentives for investment and different regulations for the  
326 areas from which feedstocks are sourced [49]. In these countries, the efforts should aim at integrated  
327 approaches across different levels, sectors, landscapes and end-uses, in order to avoid boom and bust  
328 policies as it happened for first-generation biofuels in the EU and elsewhere.

329 Nevertheless, some regional efforts to harmonize the measurement of the bioeconomy's  
330 economic significance exist. For instance, since the launch of the European Commission (EC) strategy  
331 for the bioeconomy in 2012, the EC Joint Research Centre (JRC) is monitoring jobs and turnover in  
332 the European Union bioeconomy for all the member states and sectors [50]. In order to enable  
333 achievement of the full potential of the bioeconomy, global guidelines on the measurement and  
334 regulation of the value chains could be beneficial [8]. FAO has been already coordinating the global

335 efforts towards the development of international Bioeconomy Sustainability Guidelines. These could  
336 be used by the countries to measure sustainability aspects of their bioeconomy strategy and monitor  
337 the achievement of economic, social and environmental targets and priorities.

#### 338 *4.2 Bioeconomy as a means to achieve Sustainable Development Goals*

339 The bioeconomy has already been adopted by a significant number of countries as a new vision  
340 of development to decouple the economy from the fossil fuels dependence, and as a valid path  
341 towards the achievement of the Sustainable Development Goals (SDGs) and the commitments under  
342 the Paris Climate Agreement. For instance, the efficient and sustainable natural resource  
343 management is directly tied to at least 12 of the 17 SDGs and can cut GHG emissions by 60 percent  
344 by 2050 [51]. In addition, for lower income countries, better management of natural resources is often  
345 a key component of poverty eradication, climate change mitigation and resilient economic growth  
346 [52].

347 In low and middle-income countries with available biomass resources and/or well-developed  
348 primary sectors, a sustainable bioeconomy could unlock new opportunities for economic  
349 development and industrialization, and support economic and social objectives, such as reducing  
350 unemployment and expanding access to energy. For instance, in Argentina (and similarly in other  
351 Latin American countries with high feedstock availability), the increase in the value added to  
352 agricultural production can create employment and improve the competitiveness of export-oriented  
353 sectors. The agriculture sector of the region has the potential to generate productivity gains, which  
354 could result in significant improvements in countries' inclusion in international trade [11].  
355 Improvement in agricultural productivity can also play an important role in building resilience while  
356 increasing yields for farmers [36]. Countries with low labour productivity level in the bioeconomy  
357 sectors but abundant primary production and a sound manufacturing base could add value through  
358 bio-based methods of production [38].

359 The agriculture sector is also a key component of the bioeconomy strategy for middle-income  
360 countries such as Malaysia and South Africa. In Malaysia, the performance of the palm oil sector  
361 seems to somewhat determine the overall direction of Malaysian bioeconomy development [37]. In  
362 South Africa, enabling job creation through the expansion and intensification of sustainable  
363 agricultural production and processing is part of the three strategic objectives of the bioeconomy.

364 In the U.S., with both high feedstock potential and advanced industries, the bioeconomy is based  
365 both on the expansion of biomass and on 'bio-inventions' [25,53]. However, a bioeconomy vision  
366 based on the expansion of biomass can face challenges, such as the reliable availability of raw  
367 materials due to the increased climate and severe weather impacts, water availability, and stability  
368 of the markets [44].

369 In contrast, some high-income countries such as the Netherlands have excluded the agriculture  
370 and food sector from their bio-based economy strategy. The main reasons for this is the limited  
371 domestic supply of ecologically sustainable biomass, which concerns several other EU countries as  
372 well. Estimates suggest that, for the EU, the sustainable biomass supply will be enough to meet about  
373 10% to 20% of the final energy and feedstock consumption in 2030 [40]. Considering that land use is  
374 the most critical issue in sustainable biomass production, countries with limited land availability face  
375 relevant constraints. In countries with limited biomass availability, such as some Western European  
376 countries, the bioeconomy strategies focus more on biochemistry and bio-pharmacy benefiting from  
377 long-standing experience and R&D investments [50]. In countries focusing on high value-added  
378 bioeconomy sectors, bioeconomy can generate higher turnover compared to the employment  
379 generated, whereas the less value added sectors of the bioeconomy (mainly primary biomass  
380 production in agriculture, forestry and fisheries) typically generate more employment.

381 Technical innovation and new business models associated with the bioeconomy should  
382 potentially aim at decoupling economic growth from resource use also in countries with available  
383 resources [52]. A sustainable bioeconomy would not foster depletion of resources, degradation of the  
384 environment, loss of biodiversity and social injustice. As Germany recognizes in its bioeconomy  
385 strategy, the structural transition towards a bio-based economy can be successful only if it secures

386 the supply of food, it protects the environment, the climate and biodiversity, and it supports the  
387 development-policy objectives in developing countries and emerging economies [13].

#### 388 4.3 Linking goals and measurement frameworks

389 If a bioeconomy strategy aims to contribute to sustainable development and to environmental  
390 and social objectives (e.g. employment, food security, energy security, mitigation and adaptation to  
391 climate change [10]), these should be clearly included in the strategy objectives and should be  
392 measurable (by means of quantitative, qualitative or as aggregate indicators). Environmental and  
393 sustainability components in bioeconomy development approaches should be closely connected with  
394 supply and production of bio-resources, as well as with consumption patterns. In fact, the core of  
395 transformational strategies is not limited to the technological aspects, but includes behaviour change  
396 and institutional innovations for enabling settings and long-term incentives, both at the company and  
397 of international policy levels [39].

398 This study shows that a means to monitor progress in reaching the targets set in the bioeconomy  
399 policies and strategies is lacking in many countries, and the difficulty of measuring it can be a  
400 consequence of the lack of a clear definition of the bioeconomy concept and of concrete and  
401 measurable objectives. In fact, strategies often show non-measurable objectives and qualitative  
402 targets. In the case of South Africa and United States, for example, the suggested output indicators of  
403 critical factors to monitor bioeconomy strategy [23] and the bio-based economy indicators and  
404 composite indicators [27] have not been measured in the practice yet due to the lack of sufficient data.

405 Most countries monitor bioeconomy progress just with economic values and shares of GDP,  
406 while other aspects of sustainability and resource availability are addressed only to a limited extent  
407 [54]. The GDP is a parameter which certainly gives information on the bioeconomy contribution to  
408 the economy; however, it is not ideal due to the inadequacy of the standard industrial classification  
409 systems to systematically monitor bio-based production; the lack of systematic data and the often  
410 scattered information collected at national level. In addition, the GDP is being increasingly criticized  
411 as an inappropriate indicator to measure sustainable development since it includes activities  
412 considered detrimental to humans and the environment, and does not take into consideration social  
413 aspects that define human well-being, nor the environmental aspects (which are all important  
414 information to assess the real contribution to the overall economy). Moreover, the GDP does not  
415 include transfer payments, such as subsidies for fossil fuels [55].

416 In addition to GDP, other economic indicators often used to measure bioeconomy are: turnover  
417 (revenue from sales), employment, resource use (crops, wood, waste, land, capital, etc.), primary  
418 production of biomass in the country (agriculture, forestry, residues, fisheries, waste), import of  
419 biomass to the country, global land use for biomass based consumption in the country, production  
420 of bio-based products, price of biomass and bio-based products, consumption of bioeconomy  
421 products and trade flows [18,27,35,50]. Further indicators focus on the drivers of innovation, such as  
422 investments and spending in R&D or intellectual property. However, it can be difficult to capture the  
423 impacts of a new innovation due to a time lag between investments and outcomes. These types of  
424 indicators could be used to compare country performance in the development of a bioeconomy (e.g.  
425 which countries have a bioeconomy strategy or have dedicated R&D funds).

426 Some countries currently measure only the effect of bio-based *products* on the GDP, although  
427 bioeconomy related *services* could be included in the measurement of the bioeconomy. For instance,  
428 Finland includes nature tourism, hunting and fishing as bioeconomy services in its bioeconomy  
429 strategy [56]. Also the Malaysian BCI currently measures primarily revenues and economic flows,  
430 but it could be improved to take bio-services into account as well as broader socio-economic or  
431 environmental aspects. For instance, the BCI could incorporate measures of poverty reduction or  
432 income inequality in the bioeconomy industry, it could account for CO<sub>2</sub> emissions, or level of local  
433 biodiversity [43].

434 Nevertheless, some efforts to develop measurable social and environmental indicators to  
435 monitor the bioeconomy exist. For instance, Italy has developed a set of sustainability indicators with  
436 measurable impacts on food security, natural resources sustainability, dependence on non-renewable

437 resources, climate change, in addition to economic growth [57]. These indicators on sustainability  
438 dimension are based on the results of Systems Analysis Tools Framework for the EU Bio-Based  
439 Economy Strategy (Sat-BBE) consortium [35]. In order to measure the environmental impact of the  
440 bioeconomy, the EC JRC has developed and integrated modelling framework (IMF) to implement the  
441 consequential life cycle assessment (C-LCA). This framework identifies the consequences that a  
442 decision in the foreground system has for other processes and systems of the economy, both in the  
443 analysed background system and on other systems outside the boundaries, and allows policy impact  
444 assessment once it is fully implemented [47]. However, data gaps still need to be filled and concepts  
445 and methodology, including the IMF for the environmental impact assessment, need to be further  
446 developed and implemented.

447 Other environmental assessment and environmental management techniques include carbon  
448 footprinting, eco-audit, environmental and social impact assessment, and strategic environmental  
449 assessment [58]. An ongoing project, *MontBioEco* (from the Natural Resources Institute Finland  
450 (Luke), the Standing Committee on Agricultural Research (SCAR) Bioeconomy Strategic Working  
451 group (BSW), and CASA Ministry of Agriculture and Forestry Finland (MMM)) is developing a  
452 synthesis on bioeconomy monitoring systems in the EU Member States, including indicators and sub-  
453 indicators. The analysis has currently developed 22 indicators and 146 sub-indicators, around five  
454 main objectives: creating jobs and maintaining competitiveness; reducing dependence on non-  
455 renewable resources; mitigating and adapting to climate change; ensuring food security and  
456 managing natural resources sustainably [59]. This assessment includes the development of  
457 measurable indicators and sub-indicators that go beyond economic monitoring.

458 In countries with an existing bioenergy or biofuels strategy, efforts towards monitoring the  
459 sustainability of bioeconomy can be linked with the previous efforts on biofuels, biomass and  
460 bioenergy. Moreover, several standard, certification and labelling initiatives already set some  
461 indications both on the 'quality' of the bio-products and on their sustainability. For instance, the  
462 USDA has developed a *Certified Biobased Product* label which certifies the carbon content of a number  
463 of bio-products. Many existing bio-product certifications and standards give indications for  
464 monitoring environmental and social sustainability.

465 A further step in monitoring bioeconomy should ideally include the measurement of taxation  
466 and regulatory support. For instance, the Dutch RVO estimates also the investment in BBE R&D  
467 through tax credits and fiscal exemptions [20].

468 Other national studies are analysing existing policy to assess how public finance, regulations  
469 and capacity building can enable growth of the bioeconomy (see for instance [60] for Thailand).

470 Bioeconomy is also an opportunity for young people and next generations, and it is often linked  
471 to improving science, technology, engineering, and mathematics (STEM) education and training  
472 programmes to meet the workforce needs. For instance, these aspects come as a key priority in the  
473 US bioeconomy strategy and the Finnish bioeconomy strategy, for which developing the bioeconomy  
474 competence base by upgrading education, training and research is a key objective [56]. Also the South  
475 African bioeconomy strategy and the indicators suggested in the strategy, being driven by the  
476 Department of Science and Technology, have an 'innovation' bias. In fact, most indicators in the  
477 strategy are related to science, technology and innovation, as they are derived from the measurement  
478 of a knowledge-based economy or biotechnology innovation policies [23].

479 Finally, in Argentina, Malaysia and South Africa, one of the bioeconomy objectives is to  
480 strengthen infrastructure to support economic growth and increase access to national and  
481 international market [10,15,23]. Therefore, this aspect should ideally be included in a pathway  
482 towards a sustainable bioeconomy monitoring including socio-economic and environmental impacts.  
483 Other aspects, such as the inclusion of gender (not mentioned as priority in any of the strategy  
484 analysed), may be included in the measurement framework, in order to reflect country's priorities  
485 and strategy.

486  
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488

## 489 5. Conclusions

490 This study underlines the lack of a homogenous definition of bioeconomy across the countries  
491 analysed, which does not allow any straightforward comparison of the relevance of bioeconomy in  
492 the different economies.

493 The sectors comprised mostly reflect priorities identified by the country and comparative  
494 advantages linked for instance to availability of natural resources, traditional industries, labour  
495 productivity and past investments in R&D. For instance, the agri-food sector is identified as a priority  
496 for Argentina, Malaysia and South Africa; while the Netherlands and the United States focus more  
497 on non-food sectors.

498 Most countries measure bioeconomy progress just with economic values and shares of GDP. On  
499 top of the lack of international consensus on which products and activities are comprised within the  
500 bioeconomy, the GDP approach has several limitations due to the inadequacy of the standard  
501 industrial classification systems to systematically monitor bio-based production; the lack of  
502 systematic data and the often scattered information collected at national level.

503 Usually, bioeconomy strategies also consider intangible aspects, such as institutional set up,  
504 policies, governance, regulations, incentives and financial instruments, which create an enabling  
505 environment for the bioeconomy, as well as social and environmental issues. Several countries  
506 emphasize the role that bioeconomy plays in their development strategy, which is an important  
507 aspect to reflect in their measurement efforts. This could allow monitoring, for instance, progress in  
508 meeting the SDGs or environmental targets. In fact, important synergies between countries  
509 commitments towards the measurement of SDGs and bioeconomy can be leveraged.

510 In order to facilitate the measurement and monitoring of bioeconomy at a national level, the  
511 governments could enhance and coordinate communication between different domestic agencies and  
512 entities and establish protocols for sharing data; formalize bio-based industry measurement  
513 standards; develop a comprehensive survey for bio-based industry and commodity usage; and  
514 review and revise industry classification systems. Ongoing efforts aim to harmonize the definition  
515 and measurement of bioeconomy, at least across macro-regions, such as the EU. These efforts will  
516 allow to have structured and comparable measurement and monitoring of the trends in bioeconomy.  
517 These efforts should go hand-in-hand with the development of relevant and comprehensive  
518 guidelines on how to measure the sustainability of the bioeconomy, possibly agreed at an  
519 international level. These sets of indicators should also consider social and environmental issues.  
520

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539

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